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Among articles to appear in early numbers of the *Journal of Geology* are the following:

The Relation of the Physical Properties of Natural Glasses to Their Chemical Composition. By William O. George.

The Character of the Stratification of the Sediments in the Recent Delta of Fraser River, British Columbia, Canada. By W. A. Johnston.

Notes on a Recent Collection of Fossil Plants from the Dalles Group of Oregon. By Ralph W. Chaney.

The Great Fault Troughs of the Antilles. By Stephen Taber.

A New Occurrence of Crystobalite in California. By Austin F. Rogers.

Fault Features of Salton Basin, California. By John S. Brown.

A New Phytosaur from the Trias of Arizona. By Maurice G. Mehl.

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THE

JOURNAL OF GEOLOGY

January-February 1922

AN OUTLINE OF THE GEOLOGY OF NEW ZEALAND[1]

W. N. BENSON
University of Otago, Dunedin, New Zealand

Pre-Silurian.—In the more recent accounts of the history of New Zealand it has been customary to consider as of Pre-Cambrian age the complex of gneisses and associated metamorphic rocks in the southwestern extremity, but the evidence for so doing is not yet conclusive, and various authors have referred the plutonic gneisses therein to different periods, extending as late as the Cretaceous. It would appear that the more probable hypotheses could be limited to two.

The first definite point lies in the proved existence of Lower Ordovician rocks in the extreme northwest and southwest of the South Island (Fig. 1).[2] These graptolitic slates are associated

[1] This outline is based on the writer's presidential address delivered to the geological section of the Australasian Association for the Advancement of Science in 1921. For detailed discussion of the most recent work, with full bibliography, reference may be had to this address. Earlier extensive accounts have been given by Marshall ("New Zealand and the Adjacent Islands," Steinmann's *Handbuch der regionalen Geologie*, Bd. VII, Abt. 1, 1912), and Park (*The Geology of New Zealand*, Whitcombe and Tombs, 1910).

[2] The map herewith (Fig. 1) has been based upon one recently issued by the Geological Survey (see *New Zealand Journal of Science and Technology*, 1921) and also incorporated in the above-mentioned address, thanks to the generous permission of the director of the geological survey, Mr. P. G. Morgan. The present copy has been somewhat modified in accordance with the view favored herein concerning the age of the Otago schists, etc.

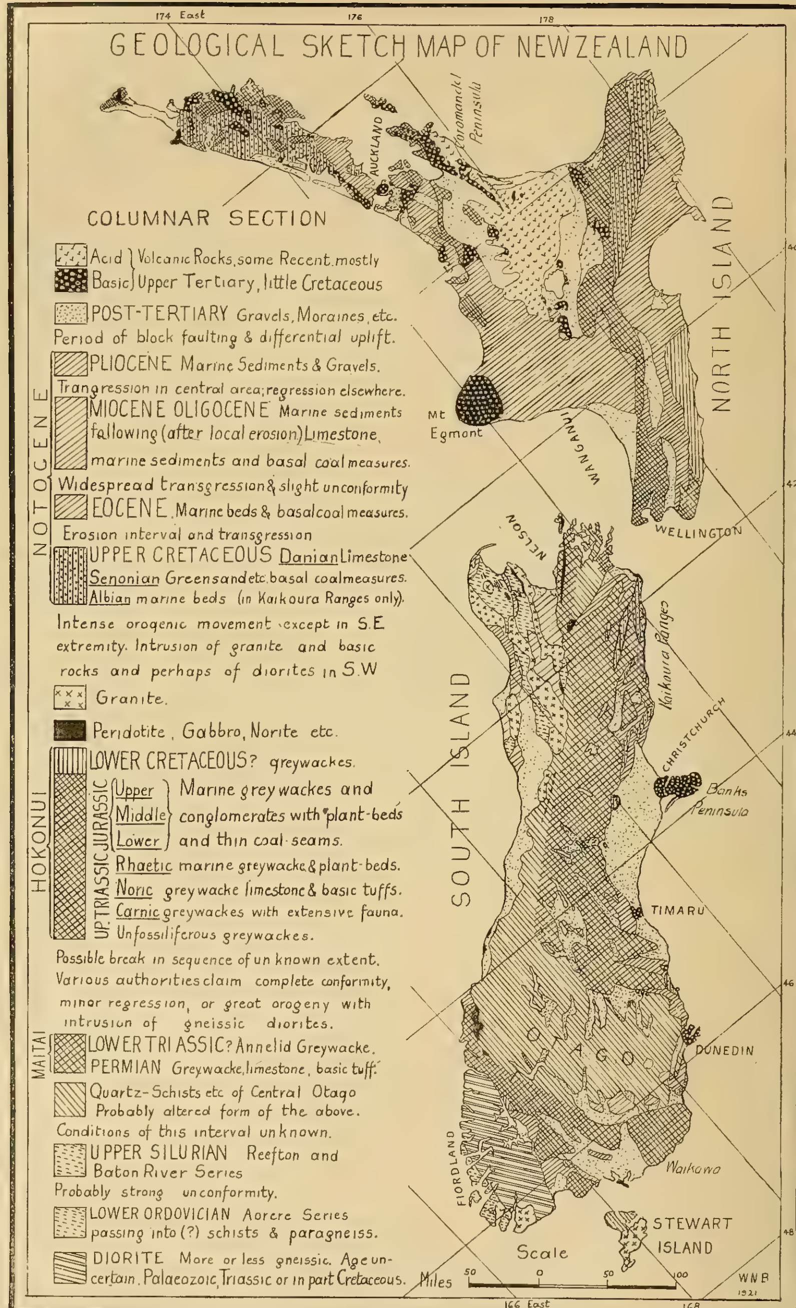

FIG. 1

Correction: Insert ? after "Erosion interval" between EOCENE and UPPER CRETACEOUS in section above.

with limestones, graywackes, and quartzites and pass with apparently gradual transition into mica-schists, which are invaded by gneissic diorites. A narrow zone of such schistose rocks extends intermittently down the west coast of the island. In the southwest the gneissic diorites become dominant and are associated in one region with "granitic" gneisses. In addition, there are massive plutonic rocks, chiefly granites, occurring especially in the two extremities of the island and surrounded by zones of contact metamorphism, which is naturally more marked where the regional metamorphism is least pronounced. The first hypothesis is that adopted by the Geological Survey. The gneissic rocks and invaded schists are considered to be of pre-Ordovician, possibly pre-Cambrian age, and covered unconformably by the Ordovician sediments. No sharp line of separation has, however, been found between them, nor other evidence of difference of age, such as the inclusion of gneissic pebbles in the Ordovician rocks. The massive plutonic rocks are considered to be of much later date, and probably later Paleozoic or even in part Mesozoic.

The second hypothesis regards the more or less gneissic dioritic rocks as having invaded the Ordovician sediments in Paleozoic or possibly Mesozoic times, before or during the climax of an orogenic movement, while the intrusion of the massive plutonic rocks followed after that climax. Within the present year massive diorite has been found to invade Lower Triassic (?) annelid-bearing graywacke. In a variant of this hypothesis advocated by Park, the subordinate mass of "granitic" gneiss is held to be intensely altered sedimentary rocks and regarded as probably pre-Ordovician, merging upward into Ordovician slates. The abundance of sillimanite in the gneiss accords with this view. Petrographical examination of the gneissic diorites on Grubenmann's principles, first applied hereto by Speight, indicates that they form the core of a folded range, for structures characteristic of deep seated metamorphism are found in the center of the massif, while those produced at lesser depths occur on either side.

Bartrum has found that pebbles of similar metamorphic rocks are widely distributed in the Mesozoic and Cainozoic rocks of the North Island, suggesting the existence of an ancient Paleozoic

platform beneath the younger formations. Their occurrence also supports the hypothesis that the dioritic rocks are not younger than early Mesozoic.

Silurian.—The fossiliferous Silurian strata are known in two localities only, both in the northwest of the South Island. They strike in a direction usually about north-northwest, the same as that of the Ordovician rocks, but their relation thereto is as yet unknown, nor are the conditions at all favorable for investigating this. In the northern of the two areas (Baton River) the rocks are calcareous argillites, but in the southern occurrence (Reefton) they are of more littoral and varied nature, with a consequent difference in faunal facies. Both faunas are apparently closely related to the Upper Silurian (Wenlock) faunas of Southeastern Australia, but have not yet been very critically examined.

"Permo-Carboniferous" and Lower Mesozoic.—No further information is available until the close of the Paleozoic era, when commenced the more nearly continuous portion of the stratigraphical record. The greater part of the mountainous country of New Zealand is made up of steeply folded and shattered argillites and graywackes, generally devoid of fossils. They contain, though rarely, lenticular masses of limestone, and also, especially in the upper portions intercalated plant beds. Widespread basic tuffs, etc., occur in the lower portion. On one higher horizon basalt flows are present. Numerous subdivisions and groupings have been proposed for this series, and Trechmann's recent paleontological work, supported by that of Arber, Wilckens, and Boehm, seems to place on a firmer basis than formerly the division of the complex into a series of formations ranging from Permian to early Cretaceous age.

Permian.—The oldest fossiliferous rocks seem to rest conformably on an extensive series of basic breccias, which are probably coeval with similar breccias which elsewhere rest unconformably on Silurian rocks. The fossiliferous beds, limestones, and argillites contain at one locality (near Nelson) a few poorly preserved shells and corals which have been compared with Eastern Australian Permo-Carboniferous (Permian) forms. Among these is a large, indefinite myalinid shell which was referred doubtfully to *Inoceramus* and

more recently to the Australian Permian form *Aphanaia,* though probably both comparisons are erroneous. Fragments of this shell, however, are widespread throughout the South Island of New Zealand, and in default of better evidence may be used to indicate the extent of Permian rocks. These are succeeded by a great thickness of graywackes in which an annelid tube is almost the sole indication of organic life. Jaworski considers this form indicative of a Triassic age. It is perhaps remarkable that there are no traces of plant beds known among these rocks. *Glossopteris* does not occur in New Zealand, though a form occurring in Upper Triassic and Jurassic beds was for a time doubtfully referred to this genus.

Triassic.—There is no clear evidence (beyond that mentioned above) of a great break, accompanied by plutonic intrusions, between the Permian and Triassic fossiliferous strata, though this has been assumed by some authorities. Probably, however, a regression of the sea occurred during Middle or Lower Triassic times, as in New Caledonia. The oldest fossiliferous Mesozoic sediments are referred to the close of the Middle Triassic, and are succeeded by fossiliferous Upper Triassic rocks, representatives of the three divisions of the Alpine-Himalayan Upper Trias, Carnic, Noric, and Rhaetic being recognizable, and each divisible into subzones. The fauna is Tethyan, with the interesting addition of the circum-Pacific form *Pseudomonotis ochotica.* In general the succession of Upper Triassic faunal zones is very similar to that of New Caledonia. The local absence of well-marked horizons gives evidence of crust-warping during Upper Triassic times, and there is a notable development of basaltic tuffs and lavas among the Noric rocks. The alternation of graywackes and argillites, and intercalation therewith of plant beds or conglomerates, indicate that these sediments were formed on a continental shelf. The flora of the region, which has been studied by Arber, was similar to the contemporaneous Australian flora, but the total number of species known in the Mesozoic rocks of New Zealand is only about a quarter of those known in Australia.

Jurassic and Early Cretaceous.—These general conditions of sedimentation were maintained during the Jurassic period, in

which, however, the plant-bearing beds became relatively more abundant in the South Island, and thin coal seams occur. Lower (Liassic), Middle (Bajoccian), and Upper (Tithonian) Jurassic marine faunas are recognized, and a sequence of small floras also, but the detailed description of the first two has not yet appeared.[1] There are also a series of sediments which are rather widespread in the east of the North Island, and are perhaps of early Cretaceous age, but may be in part Upper Jurassic. They contain *Inoceramus* in some abundance. In the western side of the island, the Jurassic rocks are followed conformably by early Cretaceous (Neocomian) plant beds, containing two angiosperms.

Orogeny.—The orogenic movement which succeeded this long-continued sedimentation reached its maximum in Lower Cretaceous time. The Mesozoic sediments were forced into broken or overturned folds, and zones of shattering were produced. The axis of such folding is for the most part approximately meridional and generally oblique to the much later warpings and fault-lines which determine the northeasterly trend of the present mountain system. Plutonic intrusions occurred in connection with this folding, among which are a series of masses of ultrabasic and basic rocks appearing at intervals from end to end of New Zealand. They are most noteworthy near Nelson in the north of the South Island, where is the type-locality of the rock dunite. The association of such intrusions with fault-zones is sometimes clear. In addition to these are granites and syenites especially well developed in the northwest of the South Island, but it is as yet problematical how much of the more or less gneissic plutonic rocks of the southwestern region should be referred to this series of intrusions. Among the minor intrusions of this period are a restricted series of lamprophyric dikes, monchiquites, etc.

Undetermined schists.—We may here describe one of the most puzzling formations in New Zealand, a broad zone of mica-schists running to the southeast from the main mountain range, through the Otago province of the South Island. These have for the most part a very flat position, but dip to the southwest and north-

[1] Trechmann and Spath have described this fauna since this paper was written. See *Quart. Journ. Geol. Soc.*, 1921.

east of the broad anticlinal axis, which reaches the sea near Dunedin. To these rocks all ages have been assigned from Archaean to Jurassic. They are not associated with plutonic rocks, but may be traced outward from a central zone of maximum schistosity, through gradually decreasing metamorphism into graywackes indistinguishable from the Ordovician or Lower Mesozoic graywackes. The Geological Survey and the majority of other authorities hold that the schists are ancient and must be separated by obscure disconformities from the Mesozoic rocks. Marshall considers the schist Mesozoic, and, after much hesitation, the writer inclines toward a modification of this view. In this it is suggested that the flat arch of metamorphic rocks is the base of a great series of recumbent folds of late Paleozoic and Lower Mesozoic rocks which were pressed against a resistant or continental mass now concealed beneath the southern portion of the island. In the front of such a series of recumbent folds one would expect to find a sharp fourfold-wrinkle of the crust, beyond which the thrusting would die away in gentle undulations of the strata lying on the resistant mass. Within the overfolded areas, block-faulting might bring down the comparatively unmetamorphosed rocks of the higher recumbent folds into close apposition with the more schistose rocks of the lower folded sheets (Fig. 2). These expecta-

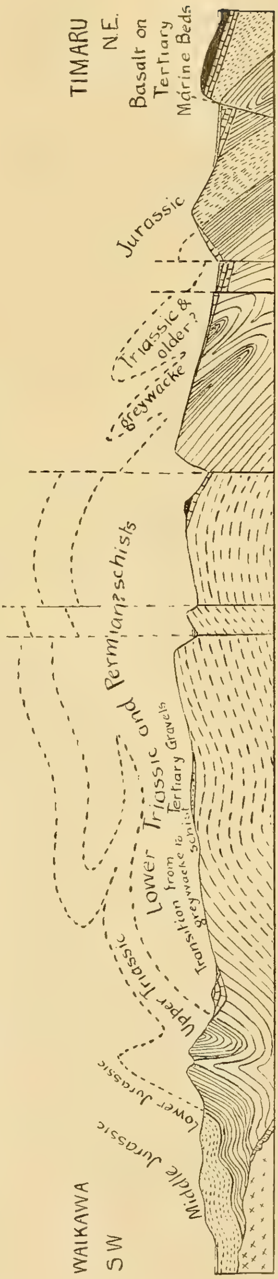

FIG. 2.—Hypothetical section from Waikawa to Timaru across the broad "anticline" of Otago. Length, 180 miles

tions appear to be realized in some measure in the facts observed in field study. The microscopical structure of the schists is indicative of strong lateral thrust rather than static metamorphism, and an excellent series of gradational structures which link them with the graywackes has been obtained by Marshall. Moreover, the apparent absence from the graywackes of any material which seems to have been derived from the schists is a striking feature, considering their close association.

The "Notocene" Sediments.—The record of the later Cretaceous and Tertiary times has as elsewhere received diverse interpretations. The simplest among current views considers that the whole series is conformable throughout. Overlap on to an evenly subsiding but irregular surface accounts for the difference of age of the basal beds in different regions. The period of greatest submergence was the period when limestone was deposited, so that the limestones in all regions must be considered as of the same age. They are succeeded by beds of a clastic character, indicating the return of shallower conditions. On other hypotheses the whole group of formations is divided up into several unconformable series, but the ages assigned these series, and the horizons at which the unconformities were recognized, have been different in the statements of different writers, or at different times in the statements of one writer. While, therefore, there has been little dispute as to the succession of strata in any region, the history of the whole period throughout New Zealand has remained obscure.

Two new conceptions have been advanced during the last decade. Thomson has suggested the existence of "diastrophic provinces," i.e., regions throughout each of which the tectonic history has been the same, though differing from that of adjacent regions. On this hypothesis, the difference of age of basal beds depends on the overlap of formations on a subsiding uneven bed but also on the different periods at which subsidence commenced in the various provinces. The limestones are not necessarily coeval throughout New Zealand, but represent merely the rock formed at the time or times of maximum submergence in each particular province, for in some districts more than one horizon of limestone is present. So also the regression of the sea occurred

at different times, and the highest beds in one province may not be coeval with those in an adjacent province. There is no need to consider that any unconformities or disconformities of a general nature are present, though local breaks may occur. Thomson has, moreover, suggested the convenient term "Notocene" (the "Southern New" formation) to indicate the whole group of sediments laid down between the Lower Cretaceous orogenic period and that which, occurring possibly at the close of Pliocene time, ushered in the present physiographic cycle.

The areal work of the officers of the Geological Survey has given rise to the second conception. Block-faulting and tilting of the crust, which was so extensive a process of the post-Notocene

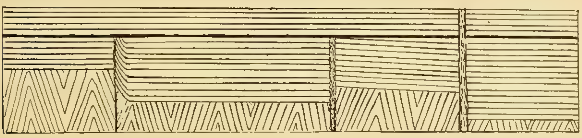

FIG. 3.—Diagram illustrating the conception of a general but deceptive conformity obscuring an erosion-interval in the deposition of "Notocene" rocks.

(Pleistocene?) orogeny, was not confined thereto, but occurred at intervals from Middle Cretaceous times onward. The movements were chiefly vertical, but along fault-planes the strata may be much crushed or upturned. Erosion proceeded *pari passu* with elevation, and the beds laid down after such movements may rest with apparently perfect conformity on the undisturbed areas, but with small or great unconformity where lying on the eroded surface of a tilted block, or near a fault-plane, or they may cross, without disturbance a zone of fault-breccias in the underlying Lower Notocene rocks (Fig. 3). If these two conceptions be admissible, we have the explanation of much apparent conflict of evidence seen when we attempt to correlate the stratigraphical succession in various regions. We must also note that such generalizations as are in the columnar statement on the map herewith must be subject to modification in detailed application to special areas.

Later Cretaceous.—The earliest of the Notocene incursions of the sea entered a small part of the northeastern portion of the South Island in Middle Cretaceous times, flooding a very irregular surface. Sixteen species of fossils have been recognized by Woods in the deposits of this period, forms identical or allied with species typical of the general Indo-Pacific fauna of the period. What follows is not quite clear, but probably the sea retreated, and entered again in late Cretaceous times, covering a much more extensive area and submerging other portions of the northeast and also in the southeast of the South Island and the east and northern portions of the North Island. A much more extensive fauna was introduced than before, over sixty species being known, which, according to Woods, Trechmann, and Wilckens, are of the typical Indo-Pacific Senonian types, with a particularly marked affinity with the fauna of Southern America and Grahams Land. Indeed, it seems as if we must conclude that New Zealand, Antarctica, and South America lay, at the close of Cretaceous times, on the coast of the South Pacific Ocean, involving the hypothesis of a land connection at this period between these regions, a conclusion to which biologists have long tended.[1] In some parts of New Zealand the Senonian beds are followed by a great thickness of almost unfossiliferous though partly foraminiferal limestone, to which a Danian age has been assigned. This stage is, however, missing from many districts.

Eocene.—In "Eocene" times,[2] the sea spread in certain regions, but was missing from others. Three contrasted developments of beds of this epoch may be noted. At this time were formed the most valuable coal-measures in New Zealand, those in the northwestern portion of the South Island, the recent survey of which has been in large part due to Morgan. The highlands adjacent to this

[1] There is very little affinity between the Cretaceous faunas of New Zealand and Australia.

[2] The Lyellian terminology may perhaps be retained for the major subdivisions of the Notocene period, but since we do not know the relative rate of evolution of new marine forms in New Zealand and Europe, we cannot conclude that strata with like percentages of Recent forms in the two regions are coeval, and hence the terms based on such percentages can have but a local comparative value. For this reason the convention is adopted of placing them between quotation marks.

region were still unreduced, and a great thickness of conglomerate was laid down prior to the formation of the coal-measures, which in turn are succeeded by marine mudstones, the fossils of which contain less than 5 per cent of recent forms. On the other hand, in the southeastern portion of the South Island, the Upper Cretaceous coal-measures are succeeded by soft mudstones or impure limestones, which Marshall found to contain less than 10 per cent of Recent forms in rather extensive faunas, including also some characteristic early Tertiary genera. In the northeastern part of the South Island a series of marly rocks overlying the above-mentioned Danian limestone may represent this epoch.

Oligocene and Miocene.—By the close of "Eocene" times the mountains formed during the Cretaceous crust-folding had been reduced approximately to a peneplain and the marine transgressions of "Oligocene" and "Miocene" times submerged the greater portion of the South Island, and much of the North Island, and a very rich molluscan fauna was present. There was, however, considerable local variation in the development of such marine rocks, a discussion of which would necessarily lead into much detail, with the difficulties of conflicting correlations and a confused nomenclature. It should, however, be noted that in the central region of Otago in the South Island, where, it is suggested, the recumbent folds of the Cretaceous orogeny were most highly piled, reduction by erosion and subsidence seems to have been retarded, so that this region remained above the level of the Tertiary sea, but in "Miocene" and perhaps also in "Pliocene" time was largely covered with fluviatile and lacustrine deposits, often richly auriferous.

Pliocene.—Crust-warpings at the close of "Miocene" times caused the sea to retreat from the greater part of the South Island, though it transgressed on to its northeastern angle. The North Island, however, was largely if not completely submerged, except for the great volcanoes which now commenced their activity. In this transgressive sea "Pliocene" beds were laid down, in some cases with quite noticeable unconformity upon "Miocene" beds. One district calls for special mention, that of Wanganui in the southwestern portion of the North Island which must surely

become a classical district for the study of later Tertiary marine rocks in the Southern Hemisphere. A nearly continuous line of sea cliffs exposes a thickness of 3,500 feet of gently dipping clay stones. No break is seen in the succession, nor any sign of faulting, though two carbonaceous layers indicate temporary land-surfaces. Large collections of shells were made by Marshall and Murdoch at four different horizons. In the lowest were 61 per cent of Recent forms; in the next 76 per cent; in the next 90 per cent; and in the highest 93 per cent. Sands containing only modern shells rest with obvious unconformity upon this series, an almost dramatic conclusion to the Tertiary record.

Middle Tertiary faunas.—The marine faunas of Middle Tertiary times in New Zealand contain many new immigrant forms and show signs of South American influence, which scarcely are sufficient to indicate coastal connection at this time, though the affinity of the New Zealand fauna with that of South America is greater than that with Australia. Moreover, since the Middle Tertiary period New Zealand appears to have been entirely isolated.[1] The modern marine fauna is but a diminished residue of the Middle Tertiary fauna, and its specific and generic distinctness from Australian forms precludes a connection of these areas in "Pliocene" and post-"Pliocene" time.

Vulcanism.—During the Notocene period there was considerable volcanic activity. Its earliest manifestation was in a few Middle Cretaceous basaltic eruptions in the northeastern portion of the South Island, and rhyolitic extrusions, to the east and west of Christchurch, which are probably Upper Cretaceous. There are also west of Christchurch some post-Jurassic, pre-Senonian andesites, the relations of which are now being investigated. The products of early and middle Tertiary activity are much more important and widespread. Economically the most important among these were the andesites and dacites[2] of the Coromandel Peninsula, North Island, in which post-magmatic solutions have developed great auriferous deposits. Rhyolites also occur in this

[1] It is of interest to note in this connection that characteristic genera of modern New Zealand plants are represented among the Tertiary fossil leaves in Grahams Land.

[2] Included with the basic volcanic rocks in map herewith.

complex. Somewhat later were the eruptions of basalt, etc., which formed Banks Peninsula, described by Speight, and the basalts and varied alkaline rocks about Dunedin, which Marshall has studied. In Upper Tertiary times volcanic activity broke out in the center of the North Island, where it has continued to the present time. Andesites, and more or less pumiceous rhyolites, are the chief products of this activity, the principal centers of which are arranged on a line following the northeasterly "grain" of the country. Mount Egmont, the great isolated cone in the west of the island, also consists of andesite.

Pleistocene diastrophism.—The period which followed the cessation of Notocene sedimentation, though comparatively short, was that during which New Zealand assumed its present form as a result of a great series of differential movements, warping or tilting of crust-blocks, and the denudation of the surface so produced. The nature of these processes has been elucidated by Cotton. The boundaries of the several blocks are now marked by fault-scarps in homogeneous structures, or by faulted contacts of older and younger strata, at which the latter are often steeply upturned. Usually the faults are oblique to the strike of the folded strata they truncate, and very frequently extend in a northeasterly direction. The movement was not all due to simple tension and differential subsidence of blocks, but strong compressive lateral thrusts also occurred, with the occasional production of folding passing into faults, of overthrusting and even overfolding (Fig. 4).

The faults present the following characteristics. The movement even along the same dislocation, may be concentrated in a single fracture with walls close together, or perhaps several chains apart, the intervening space being filled with comminuted rock. Again the fault may be a shear-zone. . . . .

One type of fault constantly recurs: narrow trough-faults in which the rock between the main fault-walls belongs to a higher horizon than the walls themselves. When the Tertiary beds which overlie the more ancient sediments and graywackes are involved, the recognition of this type of fault is very easy. [Henderson.]

The surface of New Zealand at the close of the Pleistocene orogeny was thus that of a group of variously elevated earth-blocks

composed usually of hard graywacke or schist, on the more or less planed surface of which rested much less resistant Tertiary and sometimes Cretaceous sediments. In many elevated blocks the hard basement rocks rose to a higher level than the comparatively weak covering strata in the adjacent relatively depressed blocks, which formed broad, fault-bounded, intermontane basins or narrow, rectilinear rift valleys, or fault-angle valleys. A consequent drainage was soon established on the broken sheet of covering rocks, which it commenced to remove. Where this process is still incomplete, topography is controlled in large measure by the variation in the resistance to erosion offered by the different strata

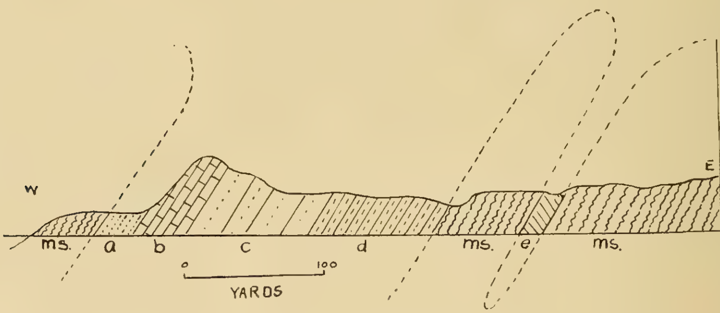

FIG. 4.—Section at Lake Wakatipu showing extensive movement in the post-Tertiary orogeny. *a*, sandstone and conglomerate; *b*, limestone; *c*, marly sandstone; *d*, marly clays; *e*, brecciated Tertiary marine rocks; *m.s.*, mica schist. (After Park.)

in the covering rocks, and dip slopes and scarps are characteristic features of the scenery. Where, however, erosion is more advanced, portions of the planed surface of the underlying rocks are laid bare, and where the cover is cleared away from extensive areas, a stripped peneplain is exposed, the further reduction of which is very slow (Fig. 5).

Late erosion.—An enormous amount of detritus results in the stripping of the covering strata from the surface of the elevated blocks and from the dissection of the fault-scarps. This is only exceptionally removed as it is supplied. In most places deep aggradation of the troughs has taken place concurrently with the dissection and degradation of the higher blocks.

As a result of this double process many interesting features have been produced in the development of the topographic forms and especially valley systems on this complex land surface. In some regions, especially those composed of the older pre-Notocene rocks, the control of the drainage by structural features is indicated by the reticulated plan of the valley systems, the association of valleys with marked lines of faulting, or with zones of fault-breccias. This is especially noteworthy where narrow masses of the softer covering strata have become involved in the fault-zone, but some control of drainage by fault-zones may be observed even in regions in which the soft covering rocks only are exposed. Probably not

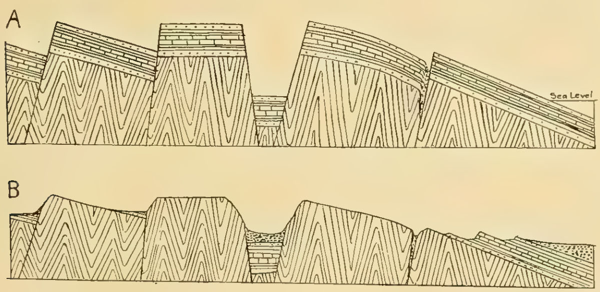

FIG. 5.—Diagram to illustrate the evolution of the present topography. *A*, effect of block-faulting of region covered by weak "Notocene" sediments; *B*, modern topography resulting from denudation of above surface and aggradation in the troughs.

only the somewhat reticulate character of the valley systems in the argillites, etc., of the northeast of the South Island has been thus influenced, but also the rectilinearly branching valleys which now form the fiords traversing the gneisses, etc., of the southwestern portion of the same island. Some of the more open, though still long and narrow depressions may be due, not merely to the differential erosion of a strip of soft material among harder rocks, but even to actual trough-faulting. The disposition of the covering rocks about one lake (Te Anau) in the southwest of the South Island affords proof of such in this particular instance.

Glaciation.—The topography does not, however, depend actively on structure and normal differential subaerial erosion, for

the effects of glaciation are also evident. It seems clear, however, that this was restricted to the highlands and the valleys among them reaching sea-level only along the west coast of the South Island. The ice did not advance to form a large confluent piedmont glacier beyond the eastern slopes of the Southern Alps, though it deployed into sheets of considerable area in the lake basins and associated depressions, notably that of the above-mentioned Lake Te Anau. The view that an ice sheet extended to the low southeastern portion of the island does not appear to be acceptable. As a result of glacial erosion, the valleys in the mountainous portions of the South Island, though originally determined as explained in the previous paragraph, have since been considerably modified. The topographic features characteristic of glaciation have been developed, and there are even indications of the effects of more than one cycle of mountain glaciation. It is not clear what extent of glaciation may have been present in the North Island, but there seems to have been little if any.

In the rain shadow of the Southern Alps an area of very small precipitation occurs in the center of the province of Otago, and here topographic features characteristic of semi-aridity may be seen.

Piedmont aggradation.—Concurrently with the degradation of the mountains, there has been much sedimentation, forming piedmont plains. A series of gravels formed during the elevation of the Southern Alps have been unconformably covered by the gravels of the Canterbury Plains. These consist of a great sheet of detritus over 130 miles long and 30 miles wide, the confluent fans of the rivers draining the eastern slopes of the mountains, at the foot of which they rise to a height of 1,000 feet above sea-level, but they have been built out over a sea floor which has subsided at least 600 feet during their formation. Less extensive plains of gravel and alluvium occur in other districts, each with special features of interest.

Loess.—Of lesser importance are the deposits of loess along the central portion of the eastern coast of the South Island. The loess is composed of the rock-flour carried by the dominant northwesterly winds from the dried pools in the braided valleys of the glacier-fed

streams, and has accumulated to a depth of 20 feet or more in suitable situations. Bones of the moa are found in these deposits.

Recent movements.—Since the epoch of great differential displacements of relatively small earth-blocks, which was the essential character of the "Pleistocene" orogeny, there have been a series of relatively small movements involving much larger earth-blocks, which movements have been elevation, depression, or tilting. Exceptionally localized differential movement has resulted in fault-coasts or strongly warped surfaces. Between these movements were long periods of crustal stability during which the cycles of erosion reached a fairly advanced stage. Hence along the coast in different districts there are marked raised beaches, while extending far up the valleys are rock-benches or alluvial terraces, indicating that the valleys are not monocyclic but were rejuvenated from time to time.

PENNSYLVANIAN STRATIGRAPHY OF NORTH CENTRAL TEXAS

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INTRODUCTION

The Pennsylvanian strata of north central Texas furnish a beautifully exposed and nearly complete section of the rocks of this period, exceedingly variable in lithologic character and prolific in well-preserved fossils. Yet because of their isolation and the semiarid, somewhat forbidding character of the country in which they outcrop, detailed study of them has been long delayed. The discovery in recent years of great deposits of petroleum within this area has brought to it many geological workers, and has served as a great stimulus to the study of the stratigraphy, differentiation, and correlation of its formations.

[1] Published by permission of the Director, Bureau of Economic Geology and Technology, University of Texas.

Previous work.—The Pennsylvanian area of Texas was first explored by Roemer[1] in 1846 and later by Shumard,[2] Ashburner,[3] and others. The most important contributions to the stratigraphy of the north Texas country, however, are contained in the writings of Tarr,[4] Cummins,[5] and Drake,[6] who made investigations of the coal fields of the Colorado and Brazos river valleys in the late eighties and early nineties for the first Texas Geological Survey.

Cummins[7] recognized six divisions in the rocks of the Texas Pennsylvanian, (1) Bend, including the black shale and limestone typically exposed in San Saba County; (2) Millsap, comprising shale, limestone, and sandstone exposed in the Brazos River Valley; (3) Strawn, including the strata, chiefly shale and sandstone, between the first coal and the base of the massive limestones of the succeeding division; (4) Canyon, the dominantly limestone division in the middle or upper part of the Pennsylvanian section; (5) Cisco, composed of shale, sandstone, and thin limestones above the Canyon limestones and below the Red Beds; and (6) Albany, consisting of thick limestones and shales above the Cisco, at first thought to belong to the Coal Measures, but later referred to the Permian. Cummins did not attempt to subdivide these large units, but the broad groups which he recognized and the names which he applied are those in use at the present time. In the main they appear to be very well chosen and the contributions of this pioneer worker based on work done under great difficulties are most important.

Drake[8] was first to make a detailed study of any portion of the Pennsylvanian in Texas. In mapping the coal field of the Colorado River Valley, he differentiated the large groups of Cummins into many smaller units which he described and named. He fixed the

[1] F. Roemer, *Die Kreidebildungen von Texas* (Bonn, 1852).

[2] B. F. Shumard, *Trans. St. Louis Acad. Sci.*, Vol. I (1860), pp. 686–87.

[3] C. A. Ashburner, *Trans. Amer. Inst. Min. Engrs.*, Vol. IX (1881), pp. 495–506.

[4] R. S. Tarr, *Texas Geol. Surv., First Ann. Rept.* (1889), pp. 201–16.

[5] W. F. Cummins, *Texas Geol. Surv., First Ann. Rept.* (1889), pp. 145–82; *Second Ann. Rept.* (1890), pp. 359–94.

[6] N. F. Drake, *Texas Geol. Surv., Fourth Ann. Rept.* (1892), pp. 357–481.

[7] W. F. Cummins, *Texas Geol. Surv., Second Ann. Rept.* (1890), p. 375.

[8] N. F. Drake, *loc. cit.*

limits of the Strawn, Canyon, and Cisco in the area studied by him, designating definite stratigraphic horizons at the top and bottom of each. Many of the subdivisions defined by Drake are employed in the present classification, but in a number of cases it has seemed necessary to depart from his usage and to apply appropriate geographic names for units to which he gave merely descriptive names, as "Cherty" or "Coral" limestone.

In addition to the investigators whose work has just been mentioned, a considerable number of geologists have reported studies of value on various portions of the Texas Carboniferous beds. Among these may be mentioned Hill,[1] Gordon,[2] Paige,[3] Udden,[4] Girty,[5] Moore,[6] and Plummer.[7] All of these investigations have been studied carefully by the writers in connection with the present work.

Recent investigations.—In December, 1916, the geologists of the Roxana Petroleum Corporation began the systematic mapping of the surface and structural geology of the northern portion of the Pennsylvanian area in Texas. As the work progressed the maps were fitted together and the data slowly compiled for a new, detailed, geological map of north Texas. At present almost the entire area of the Pennsylvanian outcrops has been mapped, the outcrops of all the principal limestones and many other beds having been traced by means of plane table and alidade. Several hundreds of geological sections have been measured and carefully described. Fossils have been collected from most of the stratigraphic divisions, those from some horizons having been studied in detail. Finally, much information has been obtained from the records of numerous wells over a large area in north Texas which have been drilled deeply into or through the Pennsylvanian.

[1] R. T. Hill, *U.S. Geol. Surv., Twenty-first Ann. Rept.* (1901), Part VII.

[2] C. H. Gordon, *U.S. Geol. Surv., Water Supply Paper 276* (1911).

[3] Sidney Paige, *U.S. Geol. Surv., Geol. Atlas, Folio 183* (1912).

[4] J. A. Udden, *Bur. Econ., Geol., and Tech., Bull. 44* (1916).

[5] G. H. Girty, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. III (1919), pp. 71–81.

[6] R. C. Moore, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. III (1919), pp. 216–52; G. H. Girty and R. C. Moore, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. III (1919), pp. 418–20.

[7] F. B. Plummer, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. III (1919), pp. 132–50.

Acknowledgments.—Cordial acknowledgment is made of the assistance of Dr. W. A. Van Waterschoot Van der Gracht, president of the Roxana Petroleum Corporation, and of Mr. Richard Conkling, head geologist, through whose courtesy the results of the stratigraphic studies of the Texas Pennsylvanian are presented. Among the geologists who have contributed importantly to the progress of the study are Messrs. John Burtt, Paul Applin, James Armstrong, Sam Wells, Chester Hammill, Angus McLeod, Grady Kirby, E. G. Allen, and Miss Linda Green.

GENERAL DESCRIPTION OF THE NORTH CENTRAL TEXAS PENNSYLVANIAN

Location.—The Pennsylvanian area of north central Texas may be described as two great inliers of Carboniferous rocks which protrude through the Cretaceous strata on the east and dip beneath Permian rocks on the west and north. The two areas are separated by a narrow tongue of Cretaceous (Trinity) sand, and the southern outcrop rests against Ordovician rocks for a short distance along the Llano uplift, so that the southern portion does not possess the relations of a true inlier.

The total area covered by the Pennsylvanian is about 7,000 square miles. It includes the west part of Montague, the southeast part of Clay, the greater portion of Jack, Young, Stephens, Palo Pinto, Eastland, Brown, the east half of Coleman, the north part of San Saba, and the northeast of McCulloch counties. The shape and location of the Pennsylvanian area are shown on the index map, Figure 1.

Lithologic character.—The lower portion of the Pennsylvanian rocks consists of massive blue, gray, or black limestone, and greenish-gray to black argillaceous and bituminous shale. As observed at the outcrop, these are not interbedded, but a division consisting almost wholly of limestone, 400 to 500 feet in thickness, lies between two shale formations. This portion of the Pennsylvanian, the Bend, contrasts in lithologic character with the remaining rocks of the system. It is the chief petroliferous horizon in north Texas.

The Millsap and Strawn divisions are dominantly clastic, the latter, especially, being composed of very massive, more or less

conglomeratic sandstones and alternating sandy shales. The resistant beds in this portion of the section are beautifully exposed over large areas in the Colorado and Brazos river valleys.

The Canyon consists of massive limestones, from a few feet to as much as 250 feet in thickness, alternating with shales. Although commonly designated a limestone division, its character is in no

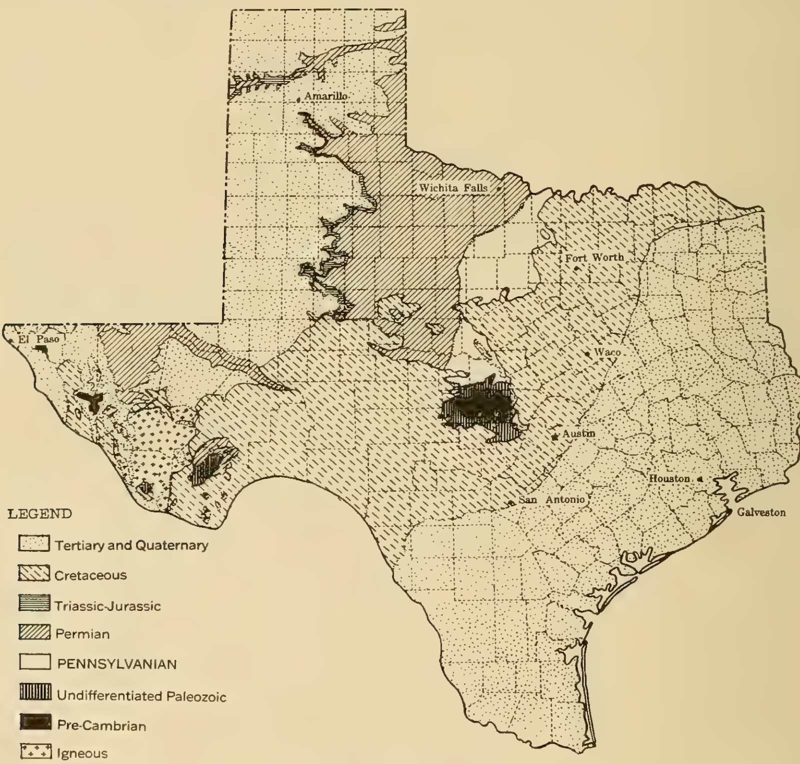

FIG. 1—Index geological map of Texas

way comparable to the Bend, for in the Canyon, the limestones are thinner and are interbedded with the shales. The limestones are hard, fine-grained, in part very cherty, and are not as a whole very fossiliferous. The shales are chiefly yellow to gray in color and clayey rather than sandy.

The Cisco is composed of thick shales and more or less conglomeratic sandstones, thin limestones, and some coal. The shale

and sand are much the most important rock types, but the limestones form persistent escarpments and are prominent, especially in the upper part and to the south. Conglomerates are found chiefly in the north. They are composed, for the most part, of small angular fragments of the resistant materials from other sedimentary formations. The shales are commonly sandy. The limestones are for the most part fine-grained and yellow to gray in color.

Thickness.—The total thickness of the Pennsylvanian of Texas, computed from measurements of the surface outcrops, is as a maximum about 6,800 feet. A compilation of average thicknesses for each of the divisions gives a total of 5,350 feet. As a matter

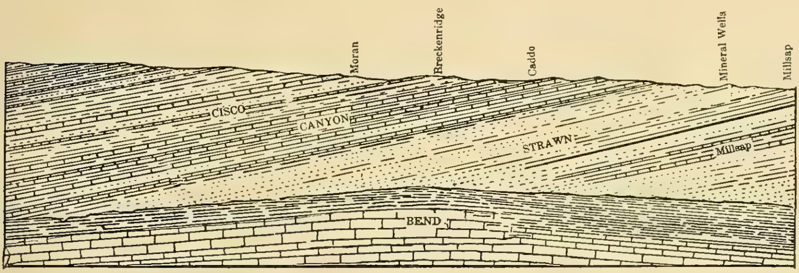

FIG. 2.—Diagrammatic section through the Pennsylvanian of Texas

of fact, the thickness of the total section is somewhat less than the total of measurements of thickness at the outcrop, for there appears to be a very important overlap of the beds from east to west, so that above the Bend the older divisions disappear successively in going to the west. This is illustrated by the diagrammatic section, Figure 2.

The average thicknesses of the divisions of the Pennsylvanian in Texas are indicated in the table of formations.

Topography.—The outcrop of the Pennsylvanian rocks and of each of the major divisions of the Pennsylvanian in north Texas is characterized by the topography. The Pennsylvanian area as a whole is distinguished by its prominent and very persistent escarpments. Due to the character of the soil and the climate, there is a widespread cover of mesquite, scrub oak, and cactus, with belts of

CLASSIFICATION OF THE TEXAS PENNSYLVANIAN

Group	Formation	Thickness in Feet	Colorado River Valley	Brazos River Valley
Cisco Group	Putnam formation	125–175	Coleman Junction limestone Santa Anna Branch shale	Coleman Junction limestone Santa Anna Branch shale
	Moran formation	150–200	Sedwick limestone Santa Anna shale Horse Creek limestone = ? Watts Creek shale	Sedwick limestone Shale Dothan limestone Shale
	Pueblo formation	150–200	Camp Colorado limestone Shale Stockwether limestone = ? Camp Creek shale	Camp Colorado limestone Shale Eolian limestone Shale
	Harpersville formation	200–275	Saddle Creek limestone Shale and coal	Saddle Creek limestone Shale Belknap limestone Shale and coal Crystal Falls limestone Shale and sandstone
	Thrifty formation	100–200	Breckenridge limestone Shale "Lower Chaffin" limestone (Drake) = ? Shale "Speck Mountain" limestone (Drake) = ? Shale and sandstone	Breckenridge limestone Shale Black Ranch limestone Shale Ivan limestone Shale Avis sandstone
	Graham formation	100–600	Wayland shale Gunsight limestone Bluff Creek shale	Wayland shale Gunsight limestone South Bend shale Bunger limestone Gonzales Creek shale Jacksboro limestone Finis shale
Canyon Group	Caddo Creek formation	30–150	Home Creek limestone Hog Creek shale	Home Creek limestone Hog Creek shale
	Brad formation	175–250	Ranger limestone Placid shale Clear Creek limestone Cedarton shale	Ranger limestone Seaman Ranch shale
	Graford formation	170–450	Adams Branch limestone Brownwood shale Capps limestone bed Rochelle conglomerate	Adams Branch limestone Brownwood shale
	Palo Pinto limestone	50–100	Not present	Palo Pinto limestone

CLASSIFICATION OF THE TEXAS PENNSYLVANIAN—*Continued*

		Thickness in Feet	Colorado River Valley	Brazos River Valley
Strawn Group	Mineral Wells formation	500–800	Undifferentiated	Keechi Creek shale Turkey Creek sandstone Salesville shale Lake Pinto sandstone East Mountain shale Brazos River sandstone Mingus shale Thurber coal
	Millsap formation	1,800–3,000		Millsap formation (undifferentiated)
Bend Group	Smithwick shale	400	Undifferentiated	Present, but not exposed
	Marble Falls limestone	400–500	Undifferentiated	
	Barnett shale	0–50	Undifferentiated	

cedar locally along the prominent limestone ridges. The area of the Bend has a rough, semimountainous topography which results from the resistant character of the massive, thick limestone of the Marble Falls formation. The Strawn area is distinguished by prominent but irregular escarpments which are produced by the hard sandstone beds. The weathering of the shales and the disintegration of the sandstone produces flat, sand-covered bottom lands, but the bold escarpments along Brazos and Colorado rivers dominate as topographic features. The Canyon, as the name somewhat fortuitously suggests, gives rise to a very rough, deeply chiseled topography which is one of the prominent geographic features of north central Texas. The massive limestone beds make high, sharp-edged escarpments which make travel from east to west very difficult. The Cisco produces a topography of gentler relief, with broad, open valleys and less prominent, though well-defined, escarpments.

Divisions.—In making the new geological map of the Texas Pennsylvanian, attempt has been made to present a classification which, conforming as closely as possible to the well-known divisions of Cummins, will apply equally to the whole area from the north to the south. Carefully measured and studied sections across the

Pennsylvanian along a number of selected lines were compared, and data gathered from mapping and evidence from invertebrate fossils were considered. The resulting classification of the sediments is shown in the following table.

BEND GROUP

The strata included in the Bend group are exposed in northern San Saba, McCulloch, western Lampasas, and Burnet counties, areas bordering the Central Mineral Region of Texas. The group is named from McAnnelly's Bend in Colorado River (Fig. 3). It consists of three formations, the Barnett shale at the base, the Marble Falls limestone in the middle portion, and the Smithwick shale at the top. The total thickness in the region of outcrop is about 850 to 900 feet.

The Barnett shale, named from springs east of San Saba, is a yellowish-gray to black, bituminous shale ranging in thickness up to 50 feet, the average being about 30 feet. Its outcrop forms a narrow, smooth pathway between the rough, broken terranes of limestone on either side, the Ellenburger (Ordovician) below and the Marble Falls above. This pathway many of the roads in San Saba County follow. Though represented in numerous well records north of the outcrop, the Barnett is not found everywhere at the base of the Bend group, as at the type locality of the Marble Falls limestone on Colorado River at Marble Falls. Where the Barnett is absent the base of the succeeding limestone commonly appears to be somewhat conglomeratic, containing débris evidently derived from the subjacent Ordovician limestones. The Barnett shale is not very fossiliferous, except locally where certain marly beds contain numerous fossils. The chief distinguishing features of the fauna are the goniatites *Glyphioceras cumminsi* and *G. incisum* and the brachiopod *Liorhynchus carboniferum*. The cephalopods, which were first described by Hyatt, Smith[1] referred to the European species *Goniatites striatus* and *G. crenistria*. Girty[2] included *G. striatus* in the synonymy of *G. choctawensis*, but it appears that the Bend fossils are most probably distinct from these. *Liorhyn-*

[1] J. P. Smith, *U.S. Geol. Surv., Mon. 42* (1903), pp. 68, 80.

[2] G. H. Girty, *U.S. Geol. Surv., Bull. 439* (1911), p. 97.

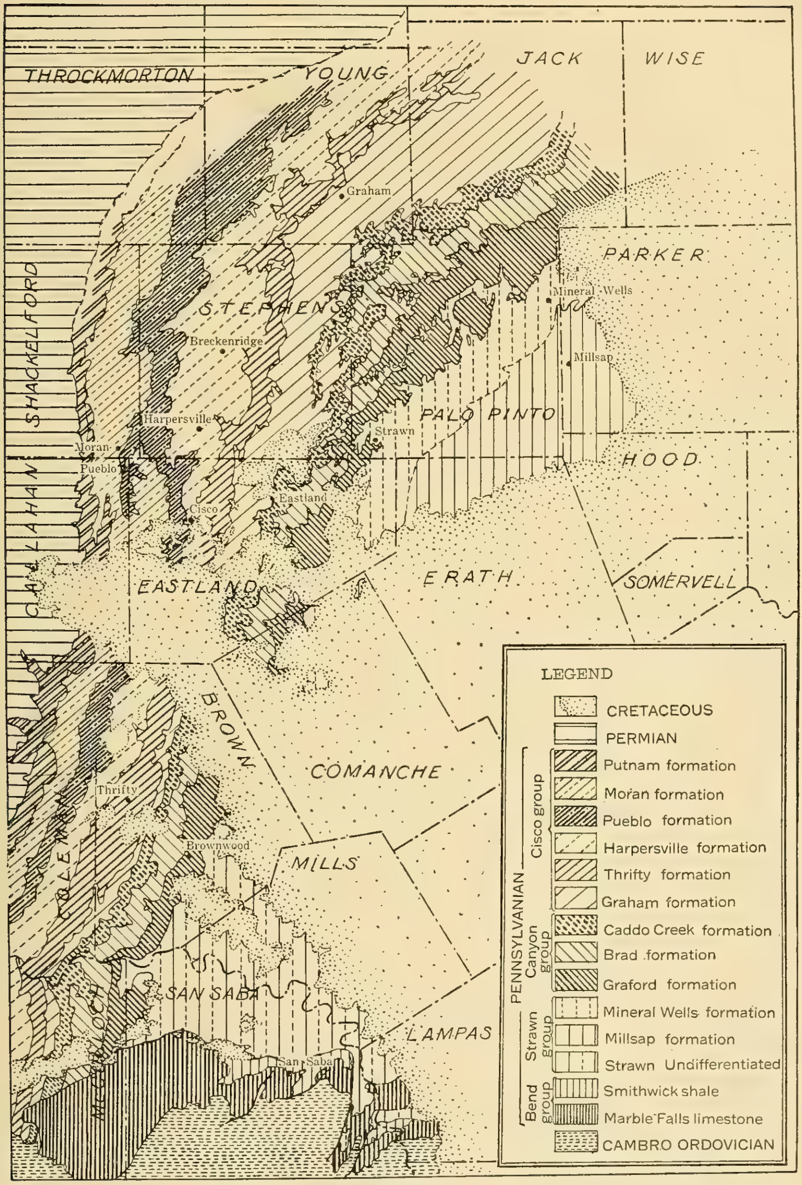

FIG. 3.—Map showing outcrops of Pennsylvanian formations in north central Texas.

chus carboniferum is reported from the Moorefield shale of northern Arkansas, in the Floyd shale of Alabama, and elsewhere in beds which are referred to the Upper Mississippian. Accordingly Girty[1] regards the Barnett as late Mississippian in age and therefore distinct from the remainder of the Bend which is undoubtedly Pennsylvanian. Goldman,[2] studying samples of cuttings from two wells north of the outcrop, believes that certain lithologic characters differentiate the lower shale, and that it is separated by a stratigraphic break from the overlying beds. Through the courtesy of the United States Geological Survey, Mr. Moore has recently had opportunity to examine particularly the contact between the Barnett and the succeeding Marble Falls divisions. It has been found that although the characteristic Barnett fauna is obtained in a limestone which apparently marks the base of the Marble Falls, there is really a sharp line of faunal demarcation between this and the Marble Falls divisions which is also distinguished by a thin zone of glauconite and phosphatic pebbles. The fauna of the Barnett is unlike that of the succeeding beds and resembles most closely that from formations which are regarded as Upper Mississippian. The Barnett shale is therefore tentatively referred to the Mississippian rather than the basal Pennsylvanian where it was placed in the previous correlation of the writers.

The Marble Falls limestone is a massive, resistant formation which is well exposed throughout the region of its outcrop. It is somewhat irregularly folded and faulted, and because of the lack of continuous exposures or readily identifiable horizons within the formation it is difficult to measure an accurate section of the unit as a whole. Its total thickness in the region of its outcrop, however, appears to be about 400 to 500 feet. In the surface exposures no sandstone and practically no shale is observed in the Marble Falls formation; but to the north well records show the occurrence of some shale interbedded with the limestone and also the presence of some limestone in the succeeding Smithwick shale. The Marble Falls limestone is but sparsely fossiliferous in some exposures, but in parts of San Saba County numerous beautifully preserved fossils

[1] G. H. Girty, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. III (1919), p. 72.

[2] M. I. Goldman, *U.S. Geol. Surv., Prof. Paper 129-A* (1921).

have been collected. Altogether more than 150 species have been identified in studies reported by one of the writers,[1] which show that in spite of a very considerable proportion of species which have not previously been described the fauna is undoubtedly representative of the Lower Pennsylvanian. Forms which are commonly found only in Mississippian strata, as the coral *Paleaçis*, occur in the Marble Falls, but the dominant element of the fauna belongs without question to typical Pennsylvanian species.

The Smithwick shale is typically a fine-grained, black or olive-green, rather fissile, bituminous formation which rests conformably upon the Marble Falls limestone. It has a total thickness of about 400 feet. Excellent exposures are found along Colorado River near Smithwick, Marble Falls, and Bend, but the outcrop is in most places marked by areas of very gentle relief where the shale has been covered by débris from weathering. The drainage, as shown in the course of San Saba River, appears to have become adjusted to the surface geology, the larger streams following the outcrop of the easily eroded Smithwick shale. Fossils are few in the black, bituminous portion of the Smithwick, but in the gray portion a varied fauna has been obtained in which the mollusks are, as might be anticipated, the dominant element. The fauna is related to that of the Marble Falls formation, but contains a number of forms not found in the beds below.

The Bend group may be correlated with the Morrow group of northeastern Oklahoma and northern Arkansas and with the horizon of the Wapanucka limestone in southern Oklahoma. Not only is there a notable similarity in the faunas of these beds, but a number of species which have been reported only from them appear to be in common. However, *Pentremites* and *Archimedes*, which have been found in both the Morrow and the Wapanucka, are not known in the Bend. As has been indicated, the Pennsylvanian aspect of the fauna is evident. If the Morrow belongs to the Upper Pottsville, as indicated by plant fossils studied by White,[2] it would appear that the Bend belongs to a late portion of

[1] R. C. Moore, *loc. cit.*

[2] David White, *U.S. Geol. Surv., Nineteenth Ann. Rept.* (1898), Part III, p. 469; *Twentieth Ann. Rept.* (1900), Part II, p. 817.

the Pottsville. On account of the unconformity and pronounced change in the character and the considerable thickness of the succeeding Strawn strata which appear certainly to be not younger than Allegheny, the writers are inclined to refer the Bend to a somewhat earlier position in the Pottsville, possibly as indicated by Ulrich,[1] the Lower Pottsville. It may be noted that some of the Bend fossils, as among the cephalopods *Paralegoceras iowense*, which are reported from other portions of the American Pennsylvanian, do not appear to be identified correctly with these species, and their significance in correlation is therefore not so important.

STRAWN GROUP

The Strawn group includes all the strata between the top of the Smithwick shale and the base of the Palo Pinto limestone in the Brazos River Valley or its stratigraphic equivalent in the Colorado River Valley. The rocks of this group are distinguished chiefly by their clastic character, especially the thickness of coarse sandstones, and by their irregularity in bedding (Fig. 4). The two main areas of Strawn outcrop, one in the valley of Colorado River and the other in the valley of the Brazos, are broadly similar, but it has not been possible to identify divisions of the one in the other. In the northern area there are exposed in the upper part of the Millsap division a number of beds of limestone which are found nowhere to the south, from which it appears that the waters of the Brazos River Valley were farther from the land of Strawn time than those of the Colorado. The entire section of the Strawn is observable along Colorado River, but in the Brazos Valley a considerable thickness of beds belonging to the lower portion of the Strawn are not exposed on account of the Cretaceous overlap from the east. In both areas there is indication of a very marked overlap of the Strawn from east to west, the successively younger strata of the group extending farther to the west than the older.

The Strawn of the Colorado River Valley lies in the area studied by Drake.[2] In his work the alternating subdivisions of sandstone and shale are differentiated in some twenty units which he termed

[1] E. O. Ulrich, *U.S. Geol. Surv., Prof. Paper 24* (1904), p. 111.

[2] N. F. Drake, *op. cit.*, pp. 375–89.

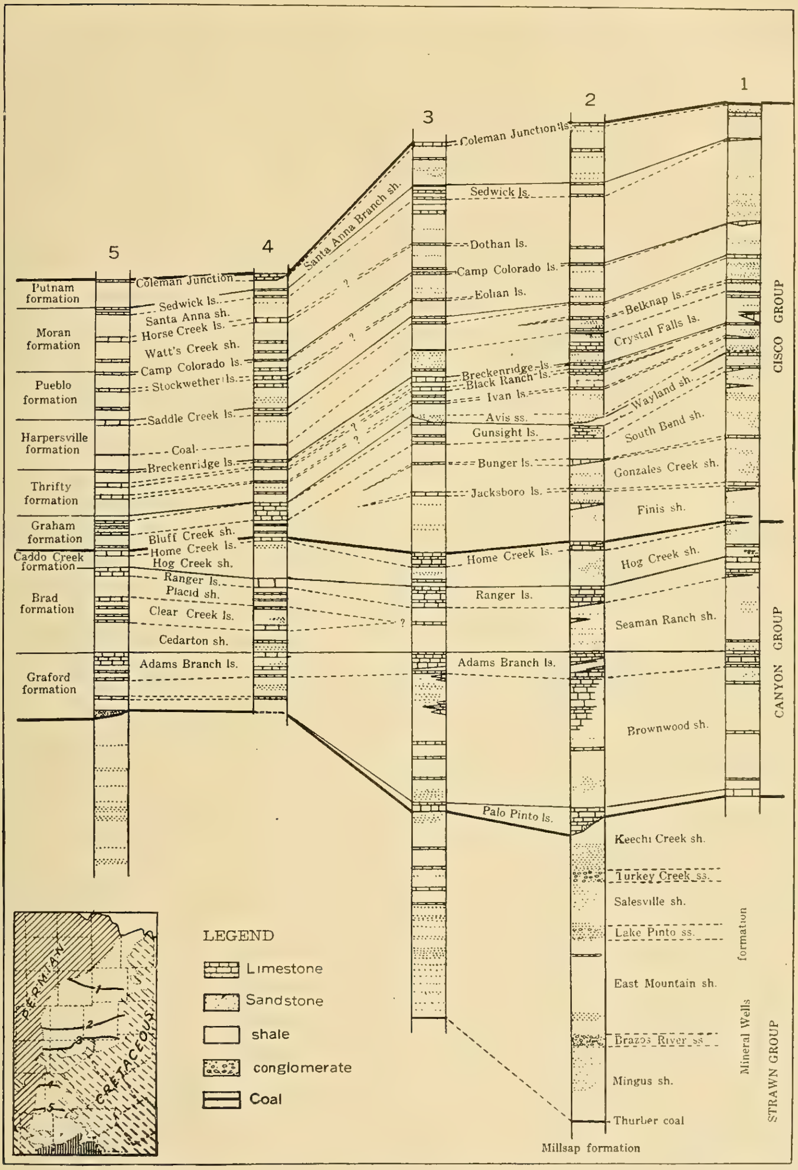

FIG. 4.—Stratigraphic sections through the Pennsylvanian of north central Texas. (1) Brownwood-Trickham section; (2) May-Coleman section; (3) Strawn-Baird section along Texas & Pacific Railway; (4) Mineral Wells-Moran section; (5) Jacksboro-Newcastle section.

beds and to which he applied stratigraphic names. The outcrops of these beds extend from south to north across the Strawn area, the dip being more or less steeply to the west. The sandstones form escarpments, but because of variations in the deposits these are very irregular and are not readily traceable or easily differentiated, as are the limestone escarpments higher in the section. The thickness of the Strawn in the Colorado River Valley as determined from measurements at the outcrop is more than 3,800 feet, but the drill shows that the greatest thickness south of Brownwood is not more than 1,200 feet. Wells 5 miles west of Brownwood show a thickness of the Strawn amounting to 700 feet, and 9 miles north of Coleman only 500 feet. Near Brady the Strawn is apparently not represented, and higher divisions of the Pennsylvanian rest directly upon the Bend.

In the Brazos River Valley two main divisions of the Strawn have been identified, the Millsap formation below and the Mineral Wells formation above. Only the upper portion of the Millsap formation is exposed at the surface, outcrops being found in the eastern part of the Strawn area near Millsap and along Brazos River in southwestern Parker County. The limestones which appear in this part of the section are quite unlike any beds observed in the Mineral Wells formation. Cummins[1] defined the Millsap division in 1890 to include all the beds in the Brazos River Valley below "coal seam No. 1" (Thurber coal) and the top of the black Smithwick shale. Thus the lower portion of the Millsap formation is known only from drill records. As a whole, the formation consists mostly of dark blue and clayey shale, limestone, and several thin, light-colored, friable sandstones. Locally it contains oil and gas in commercial quantities. Well records show its thickness in the Strawn area to range from 1,800 to 3,000 feet, and as in the case of the Strawn of the Colorado River Valley the thickness diminishes to the west: 2,200 feet at Brad in Palo Pinto County; 1,600 feet at Caddo in Stephens County; and 800 feet at Breckenridge, Stephens County.

The Mineral Wells formation includes the sandstones and shales of the upper part of the Strawn in the Brazos River Valley

[1] W. F. Cummins, *Texas Geol. Surv., Second Ann. Rept.* (1890), p. 372.

above the Thurber coal. It is very well exposed in the vicinity of Mineral Wells and along Brazos River, its outcrop extending in a belt 10 to 15 miles wide from Erath to Jack and Wise counties. Four prominent sandstone members produce prominent escarpments which are the chief topographic features of the region. The shales are sandy and are at least in part very fossiliferous.

Fossils from the Strawn collected by the writers are chiefly from the Millsap and the middle portion of the Mineral Wells formation in the Brazos Valley. The fauna of the Millsap, so far as known, is not very large, nor does it contain strongly diagnostic elements, but it appears to be more closely related to that of the Bend than the Mineral Wells. A large and varied fauna is found in the Mineral Wells formation, more than 90 per cent of which is common to the Wewoka fauna of southern Oklahoma which has been studied in detail by Girty.[1] Without doubt these faunas are very closely related, but since this fauna with some minor changes occurs in the Canyon group and in the Graham formation of the Cisco, and since in southern Oklahoma it is found as low as the Hartshorn sandstone,[2] many hundreds of feet below the Wewoka formation, it is believed that the stratigraphic equivalent of the upper Strawn in southern Oklahoma is below the horizon of the Wewoka. From evidence at hand the Strawn of Texas may be correlated with beds below the Calvin sandstone of the section northeast of the Arbuckle Mountains, with the Vinita and Winslow formations of the region farther north, and probably in part the Cherokee shale of Kansas and Missouri. It is evidently of Allegheny age.

CANYON GROUP

The Canyon group includes the beds formed after the deposition of the coarse sandstones, conglomerates, shales, and coal of Strawn time, when the land to the east had been worn low, the accumulating sediments forming a series of thick limestones and fine calcareous clays, with only a few lenses of sandstone. As here defined, the Canyon group includes the strata assigned to it by Cummins[3] in his

[1] G. H. Girty, *U.S. Geol. Surv., Bull. 544* (1915).

[2] G. H. Girty, *U.S. Geol. Surv., Nineteenth Ann. Rept.* (1898), Part III, p. 541.

[3] W. F. Cummins, *Texas Geol. Surv., Second Ann. Rept.* (1890), p. 374.

section along Brazos River, that is, from the base of the massive limestone on the East Fork of Keechi Creek, now named the Palo Pinto limestone, to the top of the massive limestone which outcrops near Finis on the line between Jack and Young counties. The latter has been found to be equivalent to the Home Creek limestone of Drake in the Colorado River Valley. Conditions were more uniform in the north Texas region during the Canyon epoch, and it is possible to trace many of the stratigraphic subdivisions for very long distances. As shown in the table of formations, there are four formations in the Canyon of the Brazos Valley, in order from the bottom: Palo Pinto, Graford, Brad, and Caddo Creek; in the Colorado Valley there are three, the Palo Pinto not being represented. The total thickness of the group ranges from an average of about 500 feet in the south to 800 or 900 feet in the north. The outcrop is correspondingly wider in the north.

The Palo Pinto limestone is a thick, crystalline, dark gray rock made up typically of beds 2 to 6 inches in thickness and having a total thickness of 50 to 100 feet. It forms a prominent escarpment across Palo Pinto County and has been traced for a long distance in the Brazos Valley. It has not, however, been identified south of the Cretaceous overlap in Eastland County which separates the Pennsylvanian outcrops. The basal beds of the Canyon consist here of wave-worked sands, thin, brecciated limestone containing pebbles of black limestone, chert, and conglomerate. Evidently there was land no great distance farther south, in the region of the present Llano Mountains. The chief distinguishing feature of the fossils which have been found in the Palo Pinto formation is their very robust size, many species being represented by individuals more than twice the normal size.

The Graford formation, named from the town of Graford in northern Palo Pinto County, consists of a thick, locally very fossiliferous shale, the Brownwood member, below, and a massive escarpment-forming limestone, the Adams Branch member, above. These divisions are well developed both in the south, where they were differentiated by Drake, and in the north. The Brownwood shale is about 160 feet thick near Brownwood, but at least 400 feet near Graford. A conglomerate at the base of the formation in the

Colorado Valley has been named the Rochelle conglomerate, and a thin lentil of limestone which is traceable for a considerable distance in the lower part of the Brownwood in Brown County is named the Capps bed. The Adams Branch limestone has a thickness of 10 to 30 feet in the southern Pennsylvanian area, but northward it increases locally to more than 100 feet. A varied fauna has been collected from the Graford formation, the most numerous fossils coming from the Brownwood member. While it contains some species, in part undescribed, not known in the Wewoka fauna, and lacks many which occur in the southern Oklahoma formation, it is a local modification of this fauna and corresponds to it more closely than to any other. A thin bed about 60 feet below the top of the Adams Branch limestone, characterized by an abundance of a very elongate, emaciated *Fusulina*, has been identified throughout the extent of this member.

The Brad formation, named from Brad in Palo Pinto County, rests conformably upon the Graford. It consists of limestone and shale, a massive, very cherty limestone, the Ranger member, marking the top. The Brad formation has been traced from near Stewarton in Jack County to Brady in McCullough County, its average thickness in the north being about 225 feet, and in the south about 200 feet. The lower part of the formation consists of shale with thin limestones and some sandstone, and in the north all the strata below the Ranger limestone are included in the Seaman Ranch member. In the Colorado River Valley, however, three members are distinguished below the Ranger: the Cedarton shale and sandstone, 20 to 80 feet at the base; the Clear Creek limestone, 10 to 25 feet, next above; and the Placid shale, 30 to 50 feet, beneath the Ranger. The Ranger limestone, which was called by Drake the "Cherty limestone," is readily distinguishable because it is the only uniformly cherty bed in the Canyon. Its thickness ranges from 10 to 50 feet.

The Caddo Creek formation, named from a tributary of the Brazos in Stephens County, has been mapped from eastern Jack County southwest and south to a point near Brady. In the north its average thickness is 100 to 150 feet, in the south 30 to 50 feet. It consists of two members, both named by Drake in the Colorado

Valley, the Hog Creek shale below, and the Home Creek limestone above. The shale is rather sandy, and especially in the north grades into a thick, cross-bedded sandstone at the top. The limestone, or rather the series of thin limestones, at the top of the Caddo Creek, has a thickness of 10 to 50 feet and in the extreme northern portion of the outcrop disappears.

A review of the paleontologic evidence and the stratigraphic relations of the Canyon group leads to the conclusion that this portion of the Texas Pennsylvanian is approximately contemporaneous with the upper portion of the section described in the Coalgate area[1] of southern Oklahoma, that is, Calvin to Holdenville, and perhaps some of the subjacent beds. This includes the Wewoka formation. Since the horizon of the Calvin has been traced northeastward to the Claremore, and this in turn to the base of the Marmaton formation in Kansas, it appears that surface-mapping checks the paleontological correlation made by Girty[2] and the Wewoka formation may be regarded as equivalent to a portion of the Marmaton. The horizon of the Lenapah limestone which belongs in the upper part of the Marmaton formation has also been traced across most of Oklahoma and appears to lie just above the Wewoka.

CISCO GROUP

The upper portion of the Texas Pennsylvanian included in the Cisco group is characterized by its more clastic sediments, its thin but persistent limestones, and the presence of coal. It includes all the beds between the Home Creek limestone of the Canyon and the lowermost beds containing Permian fossils. The change in the character of the rocks in passing from the Canyon to the Cisco is evidently the result of a diastrophic movement which made shallow the waters in northern Texas and which brought into them large amounts of coarse sand and gravel, chiefly from the north, for the northern portion of the Cisco is materially thicker and more clastic than the southern portion. The total thickness of the Cisco group is about 700 to 800 feet in the southern Pennsylvanian area

[1] J. A. Taff, *U.S. Geol. Surv., Geol. Atlas, Folio 74.*

[2] G. H. Girty, *U.S. Geol. Surv., Bull. 544* (1915).

and 1,400 to 1,500 feet in the north. Six formations have been recognized in the Cisco, as indicated in the foregoing table of stratigraphic divisions, in order from the base: Graham, Thrifty, Harpersville, Pueblo, Moran, and Putnam. As a whole, the Cisco group is not more fossiliferous than other parts of the Texas Pennsylvanian, but some beds, as the upper shale of the Graham formation, are among the most fossiliferous in the mid-continent region.

The Graham formation, named from the county seat of Young County, a place already known to science on account of the unusual ammonoids which have been collected there by J. P. Smith[1] and others, appears to rest disconformably upon the Canyon beds. The older or lower members of the Graham are present only in the north, pinching out southward and being overlapped by the younger or higher members. The formation is distinguished from the underlying beds by its very clastic character and thinner limestones, and from succeeding beds by its prolific and characteristic fauna. The subdivisions of the Brazos Valley include the Finis shale and sandstone at the base, Jacksboro limestone, Gonzales Creek shale, Bunger limestone, South Bend shale, Gunsight limestone, and Wayland shale. In the Colorado River Valley there are the Bluff Creek shale, Gunsight limestone, and Wayland shale. The limestones are in each case very thin and are not so persistent as the limestones of the Canyon. The Jacksboro and Gunsight are locally characterized by an extraordinary abundance of the coral *Campophyllum torquium.* The shales, especially the Wayland shale, contain very numerous fossils which for the most part are beautifully preserved and weather out readily from the shale. The fossiliferous zone of the Wayland has been traced in some detail from northern Jack County to Brown County, a distance of some 175 miles, and at every point where suitable exposures were found the characteristic fauna was discovered. One locality a mile south of the town of Gunsight, in southern Stephens County, contains the most surprising profusion of well-preserved fossils which has come under the observation of the writers. The fauna is very closely related to that of the Wewoka formation in Oklahoma, for not only is a very large proportion of the species common to both, but a number

[1] J. P. Smith, *loc. cit.*

of rare species which may be considered as satisfactory index fossils are found in both. One very interesting element in the Graham fauna is the group of ammonoids, or, in part, true ammonites, which occurs in the Wayland shale. While a number of these have been found nowhere outside of the Graham, they are very strongly suggestive of the Permian; indeed, so much so that if the associated invertebrate fauna and stratigraphic position were less definitely certain, the containing rocks would probably be regarded as Permian. The Graham formation is referred to the Upper Coal Measures and is believed to be approximately equivalent in age to the Kansas City formation of the Kansas section. There are marked similarities in the faunas of these horizons, and each is followed by a pronounced change in fauna, marked by the disappearance of many of the common elements in the previous invertebrate groups and by the appearance of new forms such as *Enteletes hemiplicata*, *Chonetes granulifer meekianus*, and other shells, which became widely distributed and abundant in the closing portion of the Pennsylvanian. The greater thickness of the Graham formation in the north, 500 to 600 feet as compared with 100 feet or less in the south, and its much more clastic character in the north appear to be associated with the uplift of the Arbuckle Mountains in southern Oklahoma which independent studies indicate was subsequent to the time of the deposition of the Wewoka formation and long after the beginning of the Pennsylvanian.

The Thrifty formation, named from the town in central Brown County, includes the strata from the sandstone which disconformably overlies the Graham formation to the top of the limestone which forms a prominent escarpment in the town of Breckenridge, Stephens County. The formation consists of thick shales which are less fossiliferous and brighter in color than those of the Graham, limestones which are thicker and somewhat more massive than those of other divisions of the Cisco, and some sandstone and coal. It has been mapped from Jermyn in Jack County through Young and Stephens counties to the border of the Cretaceous in Eastland County. Inliers belonging to the Thrifty appear in the midst of the Cretaceous near Romney and Bethel, and it has been traced

south of the sand to the border of the Llano Mountains southwest of Brady. In the northern Pennsylvanian area its thickness is about 150 to 200 feet, in the southern, 100 to 125 feet. The formation has not been subdivided into named members, but three of the limestone beds which have been separately mapped for long distances have been differentiated. The Breckenridge limestone, 3 to 5 feet thick, occurs at the top, the Black Ranch limestone, about the same in thickness, is found 20 to 40 feet below the top, and the Ivan limestone, 50 to 80 feet below the top. The two lower beds have not definitely been identified in the Colorado Valley, though they are possibly equivalent to Drake's "Lower Chaffin" and "Speck Mountain" limestones.

The Harpersville formation is named from a small town 10 miles south of Breckenridge in Stephens County. It includes the strata from the top of the Breckenridge limestone to the top of the Saddle Creek limestone of Drake, and is chiefly characterized by its content of one of the important workable coals in the north Texas Pennsylvanian, "Coal No. 6" of Texas reports. The shales which are the chief constituent rock are carbonaceous and ferruginous, containing siderite and limonite concretions, and locally abundant, well-preserved fossils. The only important limestone in the south is the Saddle Creek member, which consists of two or three beds 1 to 3 feet in thickness separated by shale; but in the north a second limestone, named the Belknap, 30 to 50 feet below the top of the formation, is traceable for a long distance; and in the vicinity of Crystal Falls, Stephens County, a third bed, the Crystal Falls limestone, occurs 60 to 80 feet lower. The total thickness of the Harpersville formation is 200 to 275 feet. The fauna is a fairly large one, but it is very unlike that of the lower portion of the Cisco described in the Graham. The species most common there are here missing, and new species, as *Enteletes hemiplicata*, *Chonetes granulifer meekianus*, *Derbya cymbula*, and other forms, appear. Also species which are present in the lower rocks as a rather unimportant faunal element are here very abundant. The fauna of the Harpersville is indicative of a late portion of the Pennsylvanian. It is approximately equivalent to the Douglas or Shawnee formations of the Kansas section.

The fourth formation of the Cisco, the Pueblo, is named from a town on the Missouri, Kansas & Texas Railway in northeastern Callahan County, where the rocks of this division are typically exposed. It lies conformably upon the Harpersville formation and includes the strata to the top of the persistent Camp Colorado limestone which forms a readily traceable escarpment both in the Colorado and Brazos valleys. The thickness of the formation, which averages from 150 to 200 feet, is largely made up of gray, buff, or reddish shale. The limestone beds at the top are thin, 3 to 6 feet, but are remarkably uniform and persistent. The fauna of the Pueblo is similar to that of the subjacent Harpersville and is typical of the uppermost Pennsylvanian.

The strata above the Pueblo belong to the Moran formation which is defined to include the shale and limestone to the top of the persistent yellow limestones which outcrop typically in the vicinity of Moran, Shackleford County, and in the Moran oil field. These limestones, commonly three in number, are closely associated and are grouped together as the Sedwick member. The Sedwick beds are distinguished by widely distributed and abundant small silicified fossil casts, mainly gastropods. The Sedwick may be identified with little difficulty by reason of this peculiarity of the contained fossils, the lithologic character of the limestones, and the stratigraphic position. The average thickness of the formation is 150 feet in the south and 200 feet or more in the north.

The uppermost division of the Cisco group is named the Putnam formation, from a town in Callahan County. It includes the shale and limestone overlying conformably the Moran formation to the top of the Coleman Junction limestone of Drake which comprises the upper member of the formation. The shale which follows the Coleman Junction bed contains fossils which appear to belong to the Lower Permian, but those which have been found in the limestone are not dissimilar from those in the subjacent divisions of the Cisco. As in Kansas, there appears to be here a gradual transition from the Pennsylvanian to the Permian, and a line of division is more or less arbitrary. The Coleman Junction limestone has been selected as a conspicuous, readily traceable line of such division, but it is possible that future detailed investigations will show the presence of Permian species below this horizon. The thickness of

the Putnam formation is 125 to 150 feet in the Colorado Valley, and about 175 feet in the Brazos Valley.

The middle and upper portions of the Cisco, that is, the Thrifty formation and succeeding divisions, correspond in stratigraphic position and faunal character with the upper part of the Kansas section included in the Lansing to Wabaunsee formations. The Texas divisions cannot be correlated precisely on the basis of information at hand with the Kansas formations, but there can be no doubt as to their essential equivalence.

PHYSICAL HISTORY OF THE TEXAS PENNSYLVANIAN

Sedimentation began in the north Texas area in Pottsville time, the sea first advancing into the region probably in the very early Pottsville. Black shale and later a thick mass of limestone were widely deposited about and over the Llano region and northward probably beyond the Red River. The sea of this time was evidently an invasion from the southwest, and the faunas represent the earliest typical marine Pennsylvanian of the continent. The epoch closed with more deposition of carbonaceous muds.

At the end of Bend time the sea withdrew temporarily from the Llano region and probably from most of the north Texas area. However, there was little erosion of the soft Smithwick shale, and the unconformity which is observed at the base of the Strawn is defined mainly by the difference in strike of the younger beds, the conglomerates and very remarkable change in the character of the sediments, and the overlap of the Strawn upon the Bend. The ancient land to the east representing the northeast part of Columbia, or, as it has been termed recently, Llanoria,[1] was notably uplifted and furnished a very great amount of clastic débris to the shallow sea lying to the west. This was spread out in irregular lenses with a general delta structure, dipping westward and younger deposits overlapping the older. Coal was deposited locally. The fauna had undergone a marked change from that of Bend time and at least in the upper part of the Strawn was very closely related to the southern Oklahoma Wewoka fauna. This portion, and perhaps all of the Strawn, is referable to Allegheny time.

[1] H. D. Miser, paper presented before the Geological Society of America, December, 1920.

Clearer waters, in which calcareous muds and limestones were the chief accumulating sediments, succeeded, the Canyon group representing the second epoch of dominant limestone formation in the Texas Pennsylvanian. Some 700 or 800 feet of limestones and shales were deposited during this relatively quiet interval, the invertebrate faunas showing only changes which might be anticipated with undisturbed, clear waters. It is probable that the change to dominant limestone deposition in Texas was approximately synchronous with the similar change in the northern part of the mid-continent region above the Cherokee shale.

The beginning of Cisco time is marked by a change in the character of the sediments, a great amount of mud, sand, and gravel being swept from the north and northeast, where the orogenic movement which resulted in the formation of the Arbuckle Mountains and probably an uplift of the ancient land of Llanoria furnished an abundance of materials. The thick, relatively soft, clastic formations which compose the Lower Pennsylvanian in the Arbuckle region would first be exposed to erosion and probably furnished a large proportion of the sediment in the Graham formation of north Texas. When the Lower Paleozoic limestones of the mountain areas were exposed, limestone conglomerates were formed locally (Franks) which were strewn across the eroded edges of the earlier Pennsylvanian. Although there is an important unconformity in this part of the Pennsylvanian of southern Oklahoma, the seas do not appear to have receded more than temporarily from north Texas, for the unconformity at the top of the Graham formation is not a large one. However, the faunas underwent a striking change and throughout the remainder of the Cisco have a very evident late Pennsylvanian aspect. The middle and upper Cisco represents a continuation of mud and sand deposition with an occasional limestone bed and one or two important intervals when coal was formed. There does not appear to have been any marked change with the transition to Permian time in part of the north Texas region, but to the northwest the presence of continental Red Beds sediments characteristic of the Permian appears. In these are found the well-known reptiles and amphibians which lived on the early Permian lands and along the old shores in the north Texas region.

PLEISTOCENE MOLLUSCA FROM NORTHWESTERN AND CENTRAL ILLINOIS[1]

FRANK COLLINS BAKER
Museum of Natural History, University of Illinois

Two very interesting and important collections have recently been submitted for study by members of the Illinois State Geological Survey. They include several new forms, besides a number of species not before recorded from Illinois Pleistocene deposits, though several of these have been known from Iowa glacial deposits for many years.

In the volume on the *Life of the Pleistocene* (Baker, 1920*b*, p. 368) the author listed as extinct six species of mollusks. That so small a number of species in so large a group should have become extinct is noteworthy, but is paralleled by the plants of which seven species are extinct. It is believed by the writer that careful analysis of Pleistocene Mollusca will show that more species or varieties have become extinct than is indicated by present records. Many species have been linked with existing forms though they vary quite enough to constitute distinct species or races. It will be found that some species are abundant in Pleistocene deposits, but rare living, indicating that the species is approaching extinction.

In the study of Pleistocene fossils it is of the greatest importance that minute differences between species be recorded, for it frequently happens that two deposits contain species closely related but yet sufficiently different to indicate a difference in climate, habitat, or general environment. A case in point is *Succinea avara* and *Succinea vermeta*, two closely related species or races, the latter of which is abundant in loess deposits and other Pleistocene beds. The so-called "lumper" of species can do great harm to the study of fossil faunas, whereas the so-called "splitter," recognizing small differences, may be of real help in the discrimination of faunas and

[1] *Contribution from the Museum of Natural History,* University of Illinois, No. 20.

their relation to each other. Of the two evils, splitting is certainly the less. In the study of the material from these deposits this fact has been kept in mind and careful comparisons have been made with Recent and with other fossil species.

MATERIAL FROM THE LOESS AND OTHER DEPOSITS IN NORTHWESTERN ILLINOIS

This material was collected by Dr. Morris M. Leighton, geologist in charge of Pleistocene investigations for the Illinois State Geological Survey, during the summer of 1920. Dr. Leighton has worked out the stratigraphy of these deposits and his papers appear elsewhere. The localities and sections from which the material came are indicated below, the information being contributed by Dr. Leighton. The molluscan species contained in these strata are listed as to species and abundance. The writer has added certain notes to Dr. Leighton's data, suggested by the zoölogical content of the strata. More specific information concerning the different species will be found in a later part of this paper.

STATION NO. 1

Locality: Bluff along Farm Creek, Tazewell County, about 7 miles east of Peoria, just east of the Toledo, Peoria & Western Railway bridge, near the south line of SE. $\frac{1}{4}$, Sec. 30, T. 26 N., R. 3 W.

Material: From the deposit of loess underlying the Shelbyville till, and overlying an older leached loesslike clay and the weathered Illinoian till.

Stratigraphic horizon: Early Peorian loess.

MOLLUSCAN LIFE

Helicina occulta, common.
Oreohelix iowensis, broken pieces.
Succinea ovalis, rare, immature.

All are typical Peorian loess mollusks. This is near the type locality of Leverett's Peorian interglacial stage,[1] and these are the first mollusks to be specifically identified from this type section.

[1] Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mon. 38* (1899), p. 187.

STATION NO. 2

Locality: Road cut ¾ mile northwest of Winslow, Stephenson County, just southeast of fork in roads.

Material: Yellow calcareous sandy loess from base of cut.

Stratigraphical horizon: Probably early Peorian.

MOLLUSCAN LIFE

Succinea vermeta, a common loess fossil, usually listed as *avara.*

STATION NOS. 3 AND 11

Locality: Stephenson County, SW. ¼ of SW ¼, Sec. 28, T. 27 N., R. 9 E., about ⅛ mile northeast of Pecatonica River bridge, bank along roadside 12 to 15 feet high, mostly grass- and shrub-covered; 1 mile north and ⅛ mile east of Ridott.

Material: Exposure at one place shows yellow, loesslike clay, calcareous, about 5 feet below top. Topographically a terrace resembling the silt terrace of the Pecatonica farther downstream and in tributary ⅛ mile east. No show of bedding or lamination; possibly obliterated by slumping.

Stratigraphic horizon: Probably Wisconsin, in back water from Rock River during the deposition of the Rock River Valley train.

MOLLUSCAN LIFE

Pomatiopsis lapidaria, very abundant. *Galba obrussa,* seven broken shells. *Helicodiscus parallelus,* common.

The writer is of the opinion that this deposit may have been partly formed by wind. Two of the species are semiaquatic. *Pomatiopsis* now lives in very small streams, usually not exceeding 2 feet in width and a few inches in depth. *Galba obrussa* is semiaquatic (or amphibious) and spends as much time out of the water as in it. Its habitat is in such streams as above described, or on muddy shores bordering rivers. It does not (nor does *Pomatiopsis*) live in large bodies of water such as lakes or rivers. The writer has seen several places in Illinois, shallow rivulets in woodlands bordering streams, inhabited by these species. One such is near Mahomet on the Sangamon River. *Helicodiscus* is a typical land mollusk. The character of the deposit (loesslike), the contained

calcareous concretions, and the habitat of the contained life all point to the possibility of its being low-land loess.

STATION NO. 4

Locality: Illinois Central Railway cut, Boone County, about ½ mile northwest of depot at Irene, northeast side of cut, NW. ¼, Sec. 29, T. 43 N., R. 3 E.

Material: Where fossils were collected the drift section was as follows:

		Feet
6. Soil, dark, loessial, sparse pebbles	About	2½
5. Till, leached, dark buff clay, hard		1½
4. Calcareous till, yellow on dry surface, grayish yellow with pinkish cast on damp surface, limestone pebbles; dark till in lower 6 feet	About	15
3. Stratified, yellow, calcareous sand, no pebbles; numerous pelecypods and other mollusks	About	5
2. Blue-gray calcareous silt with numerous mollusks; exposed		2
1. Bottom of cut, uncovered		5

Stratigraphic horizon of Nos. 2 and 3: Post-Illinoian and pre-early Wisconsin, possibly Sangamon.

MOLLUSCAN LIFE

Fossils were obtained from Nos. 2 and 3 as noted:

No. 3	No. 2
. . . .	*Musculium rhomboideum*, 1, fragments
Pisidium costatum, common.	*Pisidium costatum*, abundant.
Planorbis altissimus, common.	. . . .
Galba palustris, common.	*Galba palustris*, rare, immature.
Succinea vermeta, rare.	. . . .

The blue-gray silt, No. 2, indicates a quieter body of water than the yellow sand, No. 3, and the mollusks bear out this interpretation.

STATION NO. 5

Locality: Ten rods southeast of Station No. 4, northeast side of cut.

Material: The cut shows the following section:

	Feet
11. Soil, dark, loessial, sparse pebbles	2½
10. Leached till, dark buff, clayey, hard	1½
9. Calcareous till, yellowish when dry, grayish yellow with pink tinge when damp, contains limestone pebbles	7

	Feet
8. Fine sand, no pebbles, yellow, highly calcareous	$2\frac{1}{2}$
7. Calcareous till, banded, yellow and grayish, limestone pebbles, compact	$1\frac{1}{2}$
6. Blue, gummy clay, nearly gritless in some places and pebbles up to 1 inch in others, highly calcareous	$\frac{1}{3}$–$\frac{2}{3}$
5. Fossiliferous loess, grayish to yellowish, rusty streaks near base, calcareous throughout, sand streaks, cross-bedded, dip southerly	5
4. Stratified yellow sand and gray silt with few pebbles, few fossils, discoidal, calcareous	$1\frac{1}{2}$
3. Light blue silt, pebbly, some limestone pebbles, highly calcareous; may be till	1
2. Sandy to gravelly till, yellowish to rusty, limestone pebbles, matrix calcareous	2
1. Probably till, gray with pinkish tinge, calcareous; steam shovel has worked stratum giving steeper slope than above section	7

Nos. 6 to 10 include the Wisconsin drift sheets; Nos. 1 to 3 represent Illinoian till; Nos. 4 and 5 indicate an interglacial interval between the deposition of these tills. The sand and silt (No. 4) may represent the Sangamon, and the loess (No. 5) the Peorian, although there appears to be no break between them. No. 4 has yielded two species of fresh water mollusks; *Planorbis altissimus* and *Calba palustris*, represented by but a few specimens.

STATION NO. 6

Locality: Same as Station No. 5.

Material: Taken from the fossiliferous loess No. 5 of the previous section. Separate collections were made from both the yellow and gray loesses, the mollusks in both being of the same species.

Stratigraphic horizon: Possibly Peorian loess.

MOLLUSCAN LIFE

Succinea vermeta, the common *Succinea* of the loess, occurred somewhat more abundantly in the yellow than in the gray loess. Mr. B. B. Cox, a student in the University of Chicago, collected mollusks from the loess and other deposits, though he did not discriminate betweeen the deposits. He found in addition to the above *Sphyradium edentulum alticola*, a typical Peorian loess fossil, represented by one specimen.

STATION NO. 7

Locality: Whiteside County, SE. ¼ of SE. ¼, Sec. 15, T. 20 N., R. 3 E., stream-cut bank about 50 feet northwest of small bridge.

Material: Where the fossils were collected the following section was exposed:

	Feet
5. Soil dark	½–1½
4. Loesslike clay, dirty buff to buff, leached	1–2½
3. Weathered zone, brownish, separates upper from lower material	¼
2. Loesslike clay, yellow with rusty spots, no structure	5
1. Fossiliferous clay, blue silts, dense, sticky, calcareous	1½

Stratigraphic horizon of No. 1: Probably Wisconsin in age; perhaps deposited in backwater of tributaries to the Mississippi River during deposition of the Wisconsin Valley train in the Mississippi Valley.

MOLLUSCAN LIFE

Six species of fresh mollusks (one a bivalve) and one species of land mollusks were found in the fossiliferous bed, as noted:

Fresh Water	Land
Pisidium costatum, rare.	*Succinea vermeta*, common.
Valvata sincera, abundant.	
Planorbis altissimus, rare.	
Galba palustris, rare, immature.	
Galba dalli, common.	

The *Succinea* was doubtless washed into the stream from the land. The near relative of *vermeta*, *Succinea avara*, is frequently found on vegetation bordering streams or lakes.

In the section it would be interesting to know just what the weathered zone, stratum No. 3, indicates. It possibly indicates Recent wash from the bordering hill slopes since man has disturbed the soil conditions by removing the forests.

STATION NO. 8

Locality: Carroll County, NE. ¼ of NE. ¼, Sec. 8, T. 23 N., R. 5 E., south bluff of creek valley southeast of schoolhouse. The bluff is 30 feet high and occurs in the end of a terrace spur at the mouth of a tributary valley.

Material: The bluff shows the following section:

	Feet
5. Soil and angular "float"	1– 1½
4. Silt, structure mostly obliterated, leached, conforms to the present slope	1– 3
3. Sands and silts, laminated and thin-bedded, minor lens and pocket structure; clay yellow and brown; red granite bowlder 1 foot in diameter occurs about 10 feet above creek bottom on the north side near the base of this horizon; maximum	22
2. Blue silt, fossiliferous, some brown sand	6– 8
1. Coarse, angular gravel, discontinuous in the middle portion exposed (above water level)	0– 2½

Stratigraphic horizon: Nos. 2, 3, and 4 are believed to be of Wisconsin age, formed in backwater from the Mississippi, but there is reason to assign it to Peorian age or earlier.

MOLLUSCAN LIFE

Mollusks were collected from both the silts and the sands, as follows:

Silts	Sands
Succinea vermeta, abundant.	*Succinea vermeta*, abundant.
Vertigo modesta, rare, 1 spec.	. . . .
Pyramidula shimekii, rare, 3 spec.	*Pyramidula shimekii*, rare, 1 spec.
. . . .	*Galba parva*, not common.

The land shells (including all except *Galba*) are characteristic of the Peorian loess. Their presence (especially *Pyramidula shimekii*) in this deposit beneath nearly 25 feet of other material would indicate an earlier age than the Wisconsin. The till in Carroll County is of Illinoian age, and it seems probable that the material above the till, especially Nos. 3 to 5 of the section, while deposited by the Wisconsin waters, really covered up life-remains that lived during the Peorian or Sangamon interglacial period.

In the sands and silts of stratum No. 3 (Station No. 9) three species were found, *Succinea vermeta, Vertigo modesta, Galba parva,* the *Succinea* being the only abundant species, the others very rare.

STATION NO. 10

Locality: Same as Station No. 8.

Material: Creek bank 5 feet high on south side of meander curve shows the following section:

	Feet
4. Gray silt (modern)	1
3. Black, peaty soil, fossiliferous	$1\frac{1}{4}$
2. Gray silt, compact	$1\frac{3}{4}$
1. Fine gravel, cross-bedded to water level	1

Stratigraphic horizon of No. 3: Wabash stage (pre-Recent).

MOLLUSCAN LIFE

Ten species of both land and fresh-water mollusca occurred in this peat deposit, as noted:

Water	Land
Pisidium, species, a few odd valves.	*Carychium exile*, rare.
Physa gyrina, rare.	*Vitrea rhoadsi*, rare.
Aplexa hypnorum, rare.	*Gastrocopta tappaniana*, common.
Planorbis urbanensis, not common.	*Strobilops virgo*, rare.
Galba dalli, common.	*Euconulus fulvus*, rare.

This is a typical swamp or small-pond fauna such as might be found in any quiet pond in Illinois. Such small bodies of water are common in old flood plains. The presence of *Planorbis urbanensis* is noteworthy, the species being hitherto known only from the original locality at Urbana.

STATION NO. 11

Same as Station No. 3.

STATION NO. 12

Locality: Stephenson County, Sec. 22, T. 29 N., R. 6 E., about 100 feet southeast of the fork of the roads $\frac{1}{4}$ mile northwest of Winslow, east side of road; roadcut 7 feet deep, all grassed except $1\frac{1}{2}$ feet at base.

Material: Probably entirely loess. Base shows loess interstratified with sand: yellow, fossiliferous.

Stratigraphic horizon: Not precisely known, although post-Illinoian.

MOLLUSCAN LIFE

The mollusk *Succinea vermeta* appears sparingly in the base of the section.

STATION NO. 13

Locality: Whiteside County, west line of NW. $\frac{1}{4}$ of SE. $\frac{1}{4}$, Sec. 15, T. 20 N., R. 3 E., road cut on upland spur.

Material: Shown in the following section:

	Feet
2. Soil and leached loess	$1\frac{1}{2}$–3
1. Calcareous and fossiliferous loess	6

Stratigraphic horizon: Post-Illinoian, possibly Peorian.

MOLLUSCAN LIFE

Seven species of land mollusks typical of the Iowan loess occurred in stratum No. 1, as noted:

Vallonia gracilicosta, common.
Vertigo modesta, rare (previously known as *Pupilla blandi*).
Pupilla muscorum, rare.
Gastrocopta armifera, common.
Succinea avara, common.
Pyramidula shimekii, rare.
Euconulus fulvus, rare.

DISCUSSION OF SPECIES REPRESENTED IN THE DEPOSITS

Thirty species are represented in the material collected by Dr. Leighton, three of which have not before been definitely reported from Pleistocene deposits in the state, and three others have been reported but rarely and from deposits not clearly defined stratigraphically. These are:

New Records	Rare Records
Gastrocopta tappaniana	*Vertigo modesta.*
Vallonia gracilicosta.	*Pyramidula shimekii.*
Galba dalli.	*Oreohelix iowensis.*

These collections indicate that the fauna of the loess and other deposits common in Iowa also occur in Illinois, at least in the northwestern part, and that the deposits may be rather definitely correlated with those of Iowa.

The thirty species have the following distribution as to geologic age:

TABLE I

DISTRIBUTION OF SPECIES ACCORDING TO GEOLOGIC AGE

Species	Sangamon	Peorian	Wabash
Bivalves			
Musculium rhomboideum	×	....	....
Pisidium costatum	×	....	×
Pisidium species	....	....	×
Fresh-water gastropods			
Pomatiopsis lapidaria	....	....	×
Valvata sincera	....	....	×
Aplexa hypnorum	....	....	×
Physa gyrina	....	....	×
Planorbis altissimus	×	....	×
Planorbis urbanensis	....	....	×
Galba palustris	×	....	×
Galba obrussa	....	....	×
Galba dalli	....	....	×
Galba parva	....	×	....
Land gastropods			
Carychium exile	....	....	×
Helicina occulta	....	×	....
Vallonia gracilicosta	....	×	....
Succinea ovalis	....	×	....
Succinea avara	....	×	....
Succinea vermeta	×	×	×
Vertigo modesta	....	×	....
Pupilla muscorum	....	×	....
Gastrocopta armifera	....	×	....
Gastrocopta tappaniana	....	....	×
Strobilops virgo	....	....	×
Sphyradium edentulum alticola	....	×	....
Helicodiscus parallelus	....	....	×
Pyramidula shimekii	....	×	....
Oreohelix iowensis	....	×	....
Euconulus fulvus	....	×	×
Vitrea rhoadsi	....	....	×

FRESH-WATER BIVALVES (PELECYPODS)

Musculum rhomboideum (Say). A single valve of this fragile species was found in a deposit of blue-gray silt of post-Illinoian and pre-early Wisconsin age (Sangamon?) near Irene, Boone County. It is apparently rare in Pleistocene deposits.

Pisidium costatum Sterki. This small bivalve was selected from three deposits at two localities; in yellow sand and blue-gray silt near Irene, Boone County (Sangamon age), and in the blue silty clay in Whiteside County (Wabash age). It is abundant near Irene, but rare in Whiteside County. *Costatum* is known only from Pleistocene deposits, not yet having been detected among

living *Pisidia*. It is widely distributed and has been recorded from Aroostook County, Maine (Baker, 1920*b*, p. 155), Michigan (Sterki, 1916, p. 466), and Urbana, Illinois (Baker, 1918, p. 663). These records are all Wabash (post-Wisconsin). The present records carry the species back into interglacial time.

Pisidium, species indeterminate. A few odd valves of a small *Pisidium* occurred in peat material from a flood-plain pond in Carroll County, of Wabash age (post-Wisconsin).

FRESH-WATER SNAILS (GASTROPODS)

Pomatiopsis lapidaria (Say). A mile north of Ridott, Stephenson County, in loesslike silt, this species is abundant in company with *Galba obrussa* and *Helicodiscus parallelus*. The species does not differ in any way from living forms.

Valvata sincera (Say). Abundant in blue silts in Whiteside County, apparently of Wabash age. These individuals are quite typical in everything except size, the largest specimens being almost 1 mm. less in diameter than the largest living *sincera* from Lake Winnipeg. The two measurements are:

	Altitude mm.	Diameter mm.
Recent species from Lake Winnipeg	4.5	5.5
Fossil species from Carroll County	3.5	4.5

Sincera from Urbana deposits (Baker, 1918, p. 663) are like the Carroll County forms in size. If this disparity in size should prove universal, it might be of advantage to differentiate the latter as a fossil race. Not enough material of either the Recent or the fossil *sincera* is at hand to settle this question definitely. Like the Recent forms, the fossil specimens vary somewhat in the height of the spire and in the sculpture of the whorls, there being a tendency in a few individuals to form thin, sharp ribs, as in the variety *nylanderi*. This feature is more marked in the Urbana *sincera* than in the specimens from Carroll County.

PULMONATE GASTROPODS

Physa gyrina Say. Rare in the Carroll County deposit, the specimen found being also immature.

Aplexa hypnorum (Linn.). A few very young specimens, 3–4 mm. in length, occurred with the other species in the Carroll County peat deposit.

Planorbis altissimus Baker. This small *Planorbis* occurs in sand and silt deposits near Irene, Boone County, in strata believed to be of Sangamon age, and in silt in Whiteside County, of Wabash age. It was most abundant in the Irene deposits. *Altissimus* is the common small *Planorbis* of all Pleistocene deposits. As a fossil it has recently been recognized in deposits from Maine, Michigan, Wisconsin, Indiana, Illinois, New Jersey, and Canada (Ontario). It is the species listed as *parvus* in the writer's *Life of the Pleistocene* (in most cases, although true *parvis* does occur in Pleistocene deposits) and in most references to glacial fossils. It was thought to be extinct, but recently Miss Mina L. Winslow, of the Museum of Zoölogy, University of Michigan, collected a large number of a small *Planorbis* in Devil's Lake and other water bodies in North Dakota which are apparently the same species. Conditions in these lakes are becoming severe, due chiefly to increase of alkalinity, and the species appears to be dying out in the region.

Planorbis urbanensis Baker. Six specimens of a small *Planorbis*, first described from deposits in Urbana (Baker, 1918, p. 664; 1919, p. 94), occurred in the peat deposit in Carroll County. It does not differ from the Urbana individuals and its presence in a distant part of the state indicates a rather wide distribution. It has probably hitherto been listed under the all-embracing name of *parvus*. Known only from fossil strata at present.

Galba palustris (Müller). Specimens of this protean species were found in deposits near Irene, probably of Sangamon age. These do not differ from living examples of the species. Young individuals, 4 and 6.5 mm. in length, occurred in Wabash deposits in Whiteside County.

Galba obrussa (Say). Broken specimens of this species occurred in post-Wisconsin deposits near Ridott, Stephenson County.

Galba dalli (Baker). This, the smallest of the lymnaeids, was common in the peat deposit in Carroll County, and in silt deposits in Whiteside County. The specimens are somewhat larger than the types of the Recent individuals from Indiana and there is some

variation in the height of the spire and the width of the shell. This is the first record for the species in the Pleistocene deposits of Illinois, though it is common in the Recent fauna.

Calba parva (Lea). Three lots of a small lymnaeid apparently referable to *parva* were collected by Dr. Leighton, in brown sand and yellow sand, Carroll County, and in silt, Whiteside County, the latter in post-Wisconsin deposits (Wabash age). In one lot from yellow sand (see Station No. 8) the shell is very wide and convex on the body whorl. This shell resembles Wolf's figure of his *tazewelliana*, described from deposits in Tazewell County (Wolf, 1870, p. 198, Pl. XVII, Fig. 2). This form is much more obese in the body whorl than are individuals of this species from the Recent fauna. Specimens from silt in the same section have a much narrower and more compressed body whorl, and the columella is slightly impressed. A single adult individual from Whiteside County (silt deposit) has the columella impressed so as to form a slight plait. The material at hand is not sufficient to separate these forms satisfactorily, or to indicate whether they are merely local sports or larger variations. On the whole, if these are merely individual variations, the *parva* of the late Pleistocene is much more variable than its living representative.

LAND GASTROPODS

Helicina occulta Say. A number of individuals of this species occurred in Peorian loess near Peoria. It is not a pulmonate land snail.

Carychium exile H. C. Lea. A single individual of this small snail occurred in the peat deposit in Carroll County. It is quite typical.

Vallonia gracilicosta Reinhard. Seven specimens of a *Vallonia* occurred in the loess deposit of Whiteside County that are referable to *gracilicosta*. They exactly conform to the figures by Sterki (1892, p. 256, Pl. XXXIII, Figs. 48, 49) and they agree with his description, having the fine, distinct ribs characteristic of this species, which are finer and differently spaced than those of *costata*. *Gracilicosta*, according to Shimek, is a common loess fossil in Iowa. It has not previously been positively identified from Illinois deposits,

although it probably occurs and has been listed as *pulchella* or *costata*. McGee's reference to *pulchella* from Fulton, Whiteside County (*Pleistocene History of Northeastern Iowa*, p. 448) may be this species, as it looks like that species without the aid of a powerful magnifier (Baker, 1920*b*, p. 351). It probably occurs widely distributed in northwestern Illinois. Living *gracilicosta* are known only from the West and Canada. Its abundance in the loess indicates a former greater southward extension in distribution.

Succinea ovalis Say. Fragments of a large *Succinea* from the Peorian loess near Peoria are believed to be this species.

Succinea avara Say. Several specimens of a species referable to true *avara* occurred in the loess of Whiteside County.

Succinea vermeta Say. The great majority of *Succineae* collected by Dr. Leighton are referable to Say's *vermeta*, which appears distinct from his *avara*, the spire being longer, the sutures deeper, the whorls rounder, and the aperture roundly ovate instead of long ovate. The shells referred to *vermeta* vary among themselves, but all are easily separable from typical *avara*. *Avara* as recorded from Pleistocene deposits also includes *vermeta*, the two forms not being differentiated. The two forms are said to intergrade completely in the Recent fauna, but this does not seem to be true of the Pleistocene fauna, at least as shown by the material examined. The localities represented in the collections of Dr. Leighton are:

Sangamon sand, Irene, Boone County.
Early Peorian loess, Winslow, Whiteside County.
Peorian loess, Stevenson County.
Wabash sand, Carroll County.
Wabash silt, Whiteside County.

Vertigo modesta Say. This small land shell (of which the *Pupilla blandi* Morse of the Iowa deposits is a synonym) occurred sparingly in three places, in silt and sand, Carroll County, and in loess, Whiteside County. The individuals from silt and sand deposits are apparently typical with four teeth in the aperture; but the loess specimen from Whiteside County is different from any form described. There are a columella tooth and two palatal teeth, but no parietal tooth. Pilsbry (1919, p. 128) describes a toothless and a tridentate form of *modesta* from Norton Sound,

Alaska, and the Whiteside County specimen adds another variation. Not enough material is at hand to ascertain whether this variation is anything more than local. *Modesta* (under the name of *Pupilla blandi*) is a common loess fossil in Iowa. In Illinois it has been reported from the Yarmouth stage (Baker, 1920*b*, p. 271), and from deposits in the driftless area (Baker, 1920*b*, p. 353).

Pupilla muscorum (Linn.). Two specimens from the loess of Whiteside County, apparently typical.

Gastrocopta armifera (Say). Common in loess of Whiteside County, and quite typical.

Gastrocopta tappaniana (C. B. Adams). Abundant in the peat deposit of Carroll County.

Strobilops virgo (Pilsbry). Two specimens of this small land shell occurred in the peat deposit in Carroll County. They are typical.

Sphyradium edentulum alticola (Ingersoll). A single specimen of this small species occurred in the calcareous loess in Boone County, collected by Mr. B. B. Cox. This species is reported from but two other places in Illinois. These are as follows (data from Baker, 1920*b*): Aftonian, well boring near Rock Island, cited as *Pupa alticola* (p. 240); Peorian or Wabash loess, near Galena (p. 353). Its small size has probably caused it to be overlooked in the examination of loess deposits from Illinois.

Helicodiscus parallelus (Say). Common in yellow sand of Wabash age near Ridott, Stephenson County. All of the specimens are typical.

Pyramidula shimekii (Pilsbry). This characteristic land mollusk was found in two localities, both of Peorian age, loess of Whiteside County and sands of Carroll County. But one specimen was collected in each place. *Pyramidula shimekii* is an abundant fossil in the loess of Iowa and may be said to be characteristic of the Iowan or Peorian loess. No authentic records are known from strata later than the Peorian. While it is common in Iowa, it is rare in Illinois, and records are known from but one locality other than those listed (Galena in the driftless area, Trowbridge and Shaw, "Galena Folio). It may have been listed elsewhere under the name of *Pyramidula cronkhitei anthonyi*, which

somewhat resembles *shimekii.* The specimens collected by Dr. Leighton are slightly smaller than specimens from the Iowa localities.

Oreohelix iowensis (Pilsbry). Fragments of a large land shell in the Peorian loess near Peoria are believed to be this species. This fossil has been reported several times from Illinois deposits, and as it is a characteristic loess fossil, it may be of value to list these localities for comparison.

Virginia, Cass County (listed as *Helix strigosa*), Sangamon loess (Leverett, p. 171).

Fulton, Whiteside County, Peorian loess (McGee, p. 448).

Savanna, Carroll County (Chamberlin & Salisbury, p. 285), driftless area. (See Baker, *Life of Pleistocene.*)

Euconulus fulvus (Müller). A single specimen occurred in each of two deposits, in loess, Whiteside County, and in peat, Carroll County. Both are typical.

Vitrea rhoadsi Pilsbry. Two specimens of this little snail occurred in the peat deposit in Carroll County. They were apparently typical.

WABASH DEPOSITS IN THE VALLEY OF THE ILLINOIS RIVER

Mr. Harold E. Culver, geologist of the State Geological Survey, recently obtained a very interesting collection of molluscan material from marl deposits in Grundy County. Mr. Culver has furnished the following information concerning this deposit and its relation to the associated strata:

The shells from the marl deposit were uncovered in coal stripping operations near Morris, Illinois. The pit is located in the S.E. quarter of sec. 34 of Saratoga Township (34 N., 7 E., 3d. P.M.).

TYPICAL SECTION OF UNCONSOLIDATED STRATA

	Inches
5. Swamp silts, medium to dark gray	18
4. Porous clay, bright yellow-brown in color, lower surface very uneven, and thickness variable	2
3. Marl, light gray in color	8
2. Lake muds, gray, iron-stained, porous and full of organic matter, no shells, some glacial bowlders, and in places till at the base	24
1. No. 2 coal, average	30

From the character of the deposit and its relation to the underlying material, it is clear that it is post-Marseilles in age, and has evidently been laid down in a somewhat limited depression, which was probably connected with the main Illinois Valley through a narrow outlet three or four miles to the southwest. This depression presumably constituted merely an area of overflow for the older Illinois River, and still bears somewhat of the same relation to the present stream. The deposit of marl is in places less than three inches in thickness, but probably exceeds a foot at the maximum. The areal extent is not known, but judging from the topographic relation the basin in which it was deposited covers two or three miles. It does not seem probable, however, that the marl deposit is even as extensive as this.

From Mr. Culver's description the deposit would seem to be related to the old glacial outlet from Glacial Lake Chicago, when that body of water was at one of its high stages, possibly the Calumet stage. During the Glenwood and Calumet stages the Illinois Valley was well filled with water and every little cove, inlet, or depression near the valley margin was filled with water and formed ideal habitats for fresh-water mollusks such as are now found in the deposit under discussion. Similar marl beds are known from Joliet and are now being studied. The species in the Morris deposit are mostly identical with those found in the Chicago basin (Baker, 1920*b*), and it is to be presumed that the latter area was supplied with life from the Illinois Valley. It is not impossible for the Morris deposit to be pre-Lake Chicago in age, as the mollusks in the deposit could easily have lived during the Glenwood stage of Lake Chicago.

DISCUSSION OF SPECIES

Pisidium tenuissimum calcareum Sterki. An abundant species occurring also in the deposits at Urbana.

Pisidium compressum Prime. This species is evidently rare in this deposit, only a single valve being found in picking over a half-pint of material.

Amnicola leightoni Baker. Abundant. This *Amnicola* appears to be peculiar to glacial deposits. Some of the *Amnicola* recorded from Pleistocene deposits in the Chicago basin (Baker, 1920*b*) are this species and not *Amnicola limosa*, although specimens believed to be *limosa* occur. It is recorded from Ohio (Baker, 1920*a*, p. 448),

and the species probably has a wide distribution in Pleistocene deposits, from which it has been listed as *limosa*.

Amnicola walkeri Pilsbry. A common species in this deposit. Also widely distributed.

Amnicola lustrica gelida Baker. This variety of *Amnicola lustrica* was recorded as *lustrica* variety in a previous paper on Ohio glacial mollusks (Baker, 1920*a*, p. 448). It occurs abundantly in the Gundy County deposits, at Chicago, in other parts of Illinois, in Wisconsin, and in Michigan. It is constantly separable from typical *lustrica* and should have a name to distinguish it (see Baker, 1921, p. 22). It is probably peculiar to Pleistocene time.

Valvata tricarinata (Say). Both Recent and Pleistocene carinate *Valvatae* show a large amount of variation in the degree of carination. Most of these variations have been named and but one possible combination seems unrecognized (*supracarinata*), and this has been characterized from specimens in the Grundy County deposit (Baker, 1921, p. 24). Of these possible variations, seven in all, five occur in the deposit under discussion. These are:

Valvata tricarinata (Say), common.
Valvata tricarinata perconfusa Walker, abundant.
Valvata tricarinata infracarinata Vanatta, rare, two specimens observed.
Valvata tricarinata supracarinata Baker, rare, four specimens observed.
Valvata tricarinata simplex Gould, rare, one specimen observed.

Physa anatina Lea. A common *Physa* in this deposit appears to be Lea's species, although the spire is not as high as in normal *anatina*.

Physa walkeri Crandall. Common, associated with *anatina*. Apparently typical. Both species are widely distributed in Pleistocene deposits.

Planorbis campanulatus Say. Rare, but two specimens observed.

Planorbis antrosus Conrad.

Planorbis antrosus striatus Baker. Both *antrosus* and its variety *striatus* occurred commonly, in about equal numbers. A very common species in Pleistocene deposits.

Planorbis deflectus Say. Not common. Typical of the species as found Recent.

Planorbis exacuous Say. A single specimen of this characteristic species was observed. It differs from Recent *exacuous* in having a bluntly acute periphery, hence higher whorls, and in the decided deflection of the aperture. It may be an individual variation, as but the one specimen was found.

Planorbis altissimus Baker. This common small *Planorbis* occurred abundantly in the deposit. It is the most abundant species of the genus in Pleistocene deposits.

Galba obrussa decampi (Streng). Common, but most of the material is immature.

Mr. Culver also collected a number of shells in Section 23 of the same township, in a slight depression which drains fairly well to the southwest. Mr. Culver says of this material:

> The shells lie scattered through about a foot of black mucky soil, which overlies clay which is presumably weathered Marseilles till. Although lying at an elevation considerably above the present alluvial flats of the Illinois River, this appears to be merely an accumulation of recent muds, and hence cannot be referred to the glacial epoch.

Four species are represented in the lot:

Galba reflexa Say.	*Planorbis trivolvis* Say.
Physa gyrina Say.	*Planorbis pseudotrivolvis* Baker.

All were abundant except *Planorbis pseudotrivolvis*, of which but one specimen was present. This is an interesting find, because this form of *Planorbis* is present in the Chicago deposits and is now living near Urbana (see Baker, 1920, p. 123). The fauna is one that we now find in swales or summer-dry ponds in many parts of Illinois, or in the small branches of rivers near their sources.

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THE MUDDY MOUNTAIN OVERTHRUST IN SOUTHEASTERN NEVADA[1]

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INTRODUCTION

Geologists have long recognized the fact that the region of the Basin Ranges has passed through more than one period of deformation since the middle of the Mesozoic era. The most recent important disturbance found expression chiefly in great normal faults, which divided the crust into essentially parallel mountain ranges. Within many of these mountain blocks the structure is complex. Tertiary formations are strikingly unconformable among themselves, and rest with profound unconformity on the older rocks. This great unconformity is a record of prolonged erosion following an epoch of crustal compression in Mesozoic time. The youngest rocks involved in this disturbance appear to be of Jurassic age; and therefore it is probable that the movement was contemporaneous with the folding of the Sierra Nevada and Humboldt Ranges.

The degree of deformation due to this mountain-making varies greatly in the different ranges. In some the Mesozoic and older strata appear to have been nearly horizontal before the last important period of faulting. Other ranges preserve a record of the Nevadian movement in folds of varying intensity. In the Muddy Mountains of southeastern Nevada the record consists of overturned folds and an overthrust of considerable magnitude. These structural features were recognized by the writer in the course of field work during the summer of 1919, and a brief description has appeared in another article.[2] The present paper will give a more detailed description of the overthrust (Figs. 1 and 2).

[1] Published by permission of the Director of the United States Geological Survey.

[2] *Amer. Jour. of Sci.*, Vol. L (Jan., 1921), pp. 39–62.

TOPOGRAPHY OF THE MUDDY MOUNTAINS

The Muddy Mountains are a complex range bounded by wide valleys of structural origin. From north to south the length of the range is nearly 40 miles, and the maximum width, measured from

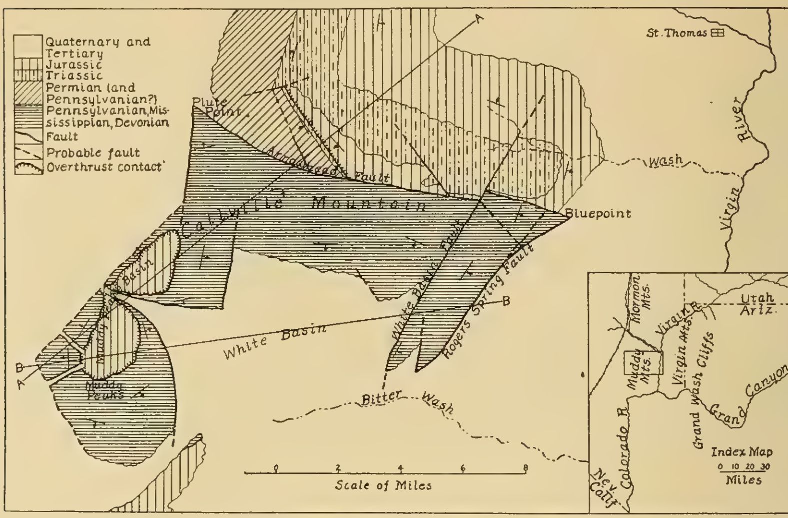

FIG. 1.—Generalized geologic map showing the Muddy Mountain overthrust

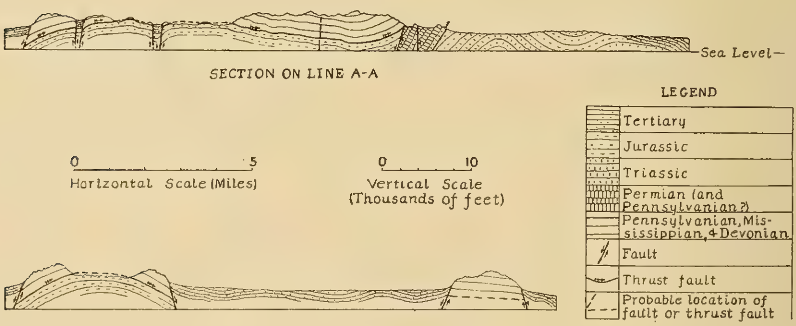

FIG. 2.—Cross sections showing structure in the Muddy Mountains

east to west, is approximately 15 miles. The intermontane valleys form a border several miles in width, with elevations ranging from less than 1000 to slightly over 2,000 feet above sea-level. The northern part of the mountains consists of ridges developed by

differential erosion on tilted strata. These ridges trend generally north and south and are elevated only a few hundred feet above the bordering valleys. Similar ridges, trending northeastward, form the southern part of the mountains. The central division consists of faulted portions of an overthrust block, and is the dominating part of the range. This division of the mountains is shaped roughly like a letter *C*, with the opening toward the south. It is a distinct unit, made conspicuous by its superior average elevation, by the abrupt faces bounding it on practically all sides, and by the dark Paleozoic limestones that form the greater part of the mass. For convenience in reference the unit has been called Callville Mountain.

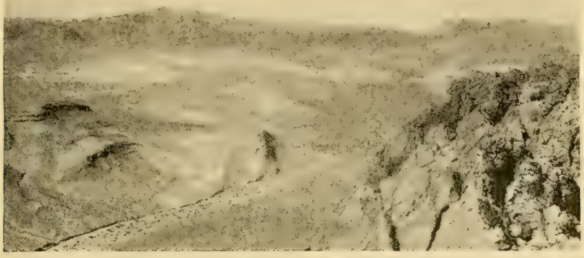

Fig. 3.—View of White Basin and part of Callville Mountain, looking northwest from the south end of the White Basin fault scarp.

Its upper surface is rugged, and a number of sharp peaks rise prominently above the general elevation. Muddy Peaks, the highest points, are nearly 5,800 feet above sea-level. Immediately north of the peaks the continuity of the mountain has been somewhat broken by faulting and erosion, and Jurassic sandstone is exposed in a depression known as Muddy Peaks Basin. White Basin, a low area floored by light-colored Tertiary deposits, lies within the curve of the *C* formed by Callville Mountain (Fig. 3).

STRATIGRAPHY

Except for small amounts of igneous materials, all of the rocks exposed in the Muddy Mountains are sedimentary. They include strata of Paleozoic, Mesozoic, and Cenozoic age. The Callville Mountain block consists of four formations, chiefly heavy limestones,

recognized as Devonian, Mississippian, and Pennsylvanian. The lowest horizon at which fossils were found lies nearly 1,000 feet above the base of the series, and therefore a part of the lower beds may belong to periods older than the Devonian. At the top of the block an unknown thickness of the Pennsylvanian beds has been removed by erosion. Outside the borders of Callville Mountain the oldest strata exposed are the upper part of the Supai formation, which is mapped (Fig. 1) with the Permian. Thus there is a gap of undetermined value in the stratigraphic succession. The following table summarizes the nature of formations and shows their relationships:

Age		Formation	Nature	Thickness (in feet)
Quaternary		Alluvial deposits	Gravel, sand, and silt	0–400
		—Unconformity—		
Tertiary	Pliocene?	Intermontane clays	Clay, silt, and sand, with salt, gypsum, and other saline deposits	200–1800
		—Unconformity—		
	Miocene?	Horse Spring formation	Limestone, clay, sandstone, conglomerate, volcanic ash, magnesium carbonate, gypsum, and other saline materials	1000–2800
		Overton fanglomerate	Coarse alluvial fan deposits, in part firmly cemented	
		—Great unconformity—		
Jurassic		Cross-bedded sandstone (equivalent to the LaPlata group)	Red and gray sandstone, with extreme cross-bedding	750–2000
Triassic		Chinle formation	Sandstone, shale, and gypsum, with some silicified wood	800–3200
		Shinarump conglomerate	Conglomerate and cross-bedded sandstone, with abundance of silicified wood	10–200
		—Disconformity—		
		Moenkopi formation	Limestone, shale, sandstone, and gypsum	1200–1600
		—Disconformity—		
Permian		Kaibab limestone	Heavy beds of limestone, with some sandstone and gypsum	400–700
Pensylvanian?		Supai formation	Red and gray sandstone, in part cross-bedded, with some gypsum and gypsiferous shale	100–800 (incomplete exposures)
Pennsylvanian		Unknown thickness not exposed		
		Callville limestone	Heavy beds of dark gray limestone, cherty in part	1100 (incomplete)
Mississippian		Bluepoint limestone	Dark carbonaceous limestone, with chert nodules	900
		Rogers Spring formation	Cherty limestone and dark gray quartzite	600
		Disconformity		
Devonian (and older?)		Muddy Peaks limestone	Heavy beds of gray limestone, in part carbonaceous	1200

STRUCTURE OF CALLVILLE MOUNTAIN

Fault boundaries.—Very evidently the steep sides of Callville Mountain are in large part due to normal faulting. Portions of the actual fault surface are well exposed, and at many points the adjacent younger formations may be seen in fault contact with the Paleozoic rocks of the mountain. The White Basin fault scarp is exceptionally well preserved. Adjacent to White Basin it is several hundred feet high, and its remarkable regularity gives it the appearance of an artificial wall. At the base of the scarp, Tertiary beds are turned steeply upward along the edge of the downthrown block, and large slickensided surfaces are numerous on the hard Paleozoic limestone of the footwall. Slickensides are distinguishable even at a height of more than 100 feet above the base of the cliff. These fault surfaces have an average westward inclination of 50°, and near its southern end the scarp as a whole has the same inclination to a height of nearly 1,000 feet. The undissected character of the scarp is due in part to the eastward tilt of the footwall block. Consequent streams on the block flow eastward, and have cut deep canyons across the Rogers Spring fault scarp, which accordingly has a much older appearance than the White Basin scarp. At the base of the Rogers Spring front the Tertiary beds are upturned steeply toward the mountain, and portions of the fault plane are exposed, dipping 60° eastward. The block east of the fault has been thrown at least several hundred feet. Thus the part of Callville Mountain included between the Rogers Spring and White Basin faults is a typical horst.

Similar faults, all with large throw, bound White Basin on the west, and at least a part of the west boundary of Callville Mountain is formed by normal fault scarps. It is very natural, therefore, to infer that the mountain is an irregular horst or group of horsts left elevated by the sinking of adjacent blocks. For the northern boundary, however, this explanation is not tenable. This side of the mountain is high and precipitous, and has the general appearance of an eroded fault scarp; but the fault plane, exposed at many points near the base of the cliff, has an average dip of nearly 70° to the south, and the older strata of the mountain have very evidently moved down with respect to the younger formations on the north.

Therefore the original topographic expression of the fault has been reversed by differential erosion. This anomalous relation indicates that the structure is more complex than is apparent at the borders of the mountain (Fig. 4).

Overthrust relations.—The key to the older structure of Callville Mountain is furnished by Muddy Peaks Basin. Pronounced doming has affected the western part of the mountain, the strata on the sides of the dome dipping at a maximum of 45°. Erosion has stripped the thick Paleozoic beds from the

Fig. 4.—Portion of the north front of Callville Mountain. In the foreground, Triassic sediments are masked by recent waste. Outcrops of Jurassic sandstone partly covered by talus near base of cliff.

summit of the dome, exposing cross-bedded Jurassic sandstone beneath. The sandstone forms the floor of an erosional basin, which has been divided into two lobes by a faulted tongue of Tertiary sediments. Limestone walls rise abruptly around the margins of the basin, and are retreating rapidly due to sapping of the comparatively weak sandstone beneath. Remnants of the limestone, lying almost horizontally, cap sandstone hills near the center of the basin. The contact of limestone and sandstone, well exposed at many places, is plainly one of overthrust, and is essentially parallel to the bedding both below and above. Immediately above the thrust surface a breccia has been developed, the thickness ranging from a few feet to at least 75 feet. Most of the fragments are of limestone, but near the base some pieces of sand-

stone are included. The breccia is well cemented with calcium carbonate, and the base is smoothly polished. Above the zone of typical breccia the limestone is intensely shattered through a thickness ranging from 100 to 500 feet. The shattered condition of the rock is responsible for the development of numerous grotesque forms by the agents of erosion.

There can be no reasonable doubt that the formation beneath the overthrust is the Jurassic sandstone, corresponding to the LaPlata group. No fossils have been found in this formation, but its lithologic features are very distinctive. The only other formation in the region that in any way resembles it is the Supai;

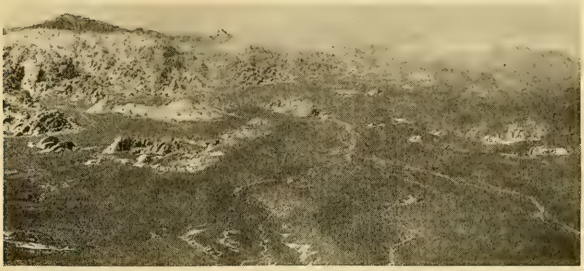

Fig. 5.—View to the northwest across Muddy Peaks Basin, showing remnants of dark Paleozoic limestone capping hills of Jurassic sandstone.

and to anyone who has studied the two formations carefully the differences are sufficiently apparent to prevent confusion. A thickness of approximately 700 feet of the sandstone is exposed in Muddy Peaks Basin, and throughout this thickness the rock has large scale cross-bedding, both straight and tangential; it has alternating laminae with coarse and fine grains; and it shows an irregular blending of red coloring with gray. All of these features are typical of the Jurassic sandstone.

Extent of the overthrust.—It is quite certain that the entire Callville Mountain mass is included in the overthrust block, although the actual surface of thrusting is exposed only in the "window" of Muddy Peaks Basin. The mountain is a unit in stratigraphy, and in all parts the lower beds show the intense shattering which is a

characteristic feature in the vicinity of Muddy Peaks. Moreover, the unusual relation of older strata to younger along the entire north side of the mountain is strong evidence of the unity of the block. The known portion of the overthrust plate, therefore, ex-

FIG. 6.—Devonian limestone, at the north end of Muddy Peaks Basin. A thickness of about 600 feet is shown. Gray Jurassic sandstone beneath the overthrust appears at the left of the view.

FIG. 7.—Close view of the overthrust contact. The hammer rests on the Jurassic sandstone. Well-cemented breccia lies above the surface of overthrust.

tends from the west side of the Muddy Peaks mass to Bluepoint, a distance of nearly 18 miles, and from Piute Point to the south side of White Basin, a distance of 10 miles. It is not possible to estimate the original dimensions of the plate. An indication that the movement affected a large area is given by the fact that the stratigraphic displacement apparent in Muddy Peaks Basin is ap-

proximately 9,000 feet, and yet the thrust surface is almost parallel to the bedding. The portion of the plate that formerly lay north of the Arrowhead fault has been removed by erosion, whereas on some other sides of Callville Mountain the strata involved in the movement have been carried downward by normal faulting.

Structural features adjacent to Callville Mouutain.—North of Callville Mountain the Mesozoic rocks form a broad anticline with its axis extending slightly north of west. Lateral movement on the White Basin fault has caused displacement of the strata within the anticline, corresponding to the offset in the north boundary of Callville Mountain. To the east the fold plunges beneath Tertiary sediments, and to the west it dies out on meeting a stronger north-south anticline which is overturned toward the east. The north-south fold is affected by a strike fault, and near Callville Mountain the structure is further complicated by overthrusting. An overturned block of Kaibab and Moenkopi limestones has been thrust toward the northeast and now lies directly on the Jurassic sandstone. The thrust plane dips to the southwest at an angle of 60°; but it is possible that its original attitude was less steep, and that its present inclination is in part due to tilting during normal faulting which has affected the block.

One structural feature south of Callville Mountain deserves special mention. Nearly a mile southeast of the Muddy Peaks mass an isolated block of Callville limestone forms a prominent ridge. The beds dip northwest at an angle of 30°, and on the south side the block is faulted down against Jurassic sandstone. This relation, which is similar to that on the north side of Callville Mountain, suggests that on the south side also the overthrust plate has been faulted down against younger formations. To what extent this is true cannot be definitely determined, because the Tertiary deposits conceal all except small portions of the older rocks. Possibly the isolated exposure of Callville limestone is only a local feature, with exceptional structural relations.

DIRECTION OF OVERTHRUSTING

No striations were found on the polished thrust surface to indicate direction of movement; but crumpling and minor thrusting in

the vicinity of Muddy Peaks Basin suggest that the overthrust plate moved from southwest to northeast. Further evidence favoring this conclusion is furnished by the strike of the minor overthrust north of the Arrowhead fault. Very probably this thrust was associated with the major movement, and had the same general direction. Some caution must be used, however, in drawing conclusions from the present strike of the smaller thrust plane, for it may have been changed considerably by the normal faults that cut the block.

GENERAL DEDUCTIONS

The east side of Callville Mountain is less than 40 miles from the Grand Wash Cliffs; and the original eastern edge of the overthrust plate was probably much nearer the western edge of the plateau. Thus there is evidence of intense compressive deformation near the border of the Basin Range region, closely adjacent to a wide area in which the effects of crustal compression are practically absent. Further evidence of the intensity of the post-Jurassic revolution in this part of Nevada is seen in the closely compressed and overturned fold extending north from Callville Mountain. This close folding and the overthrusting involve the same Mesozoic strata, and therefore may be different expressions of the same general crustal movement.

Rowe has reported an overthrust in the Spring Mountain Range, 40 miles west of the Muddy Mountains, stating that "the Carboniferous limestone is thrust over the red Mesozoic sandstone."[1] This description suggests the possibility that the feature is contemporaneous with the Muddy Mountain overthrust. It is a noteworthy fact that in a large part of the Spring Mountains and in neighboring ranges folding is gentle or practically absent. The writer ventures the suggestion that detailed mapping may show some of these ranges to be faulted portions of a great overthrust plate. Evidently the post-Jurassic revolution had a profound effect in at least a part of southern Nevada, and further field work may be expected to reveal additional evidence of the movement.

[1] Quoted by J. E. Spurr, *U.S. Geol. Survey Bulletin No. 208*, p. 177.

GROWTH-STAGES OF THE BLASTOID, *OROPHOCRINUS STELLIFORMIS*

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The references to literature are given in the *List of the Genera and Species of Blastoidea in the British Museum*, 1899.

Among the specimens entered in that *List* are some referred by Etheridge & Carpenter to *Orophocrinus stelliformis* (E 840 and E 1055), which, however do not agree well with the description by those authors or with the original figures of the species, but seem to agree more nearly with the form which Etheridge & Carpenter distinguish as var. *campanulatus* Hambach.

A set of sixteen specimens collected by Mr. D. K. Greger in the Lower Burlington Limestone at White Ledge, Marion Co., Missouri, and presented to the British Museum in 1918 by the late Dr. G. B. Longstaff (E30091–30106), if arranged in order of size, shows a complete transition from the *campanulatus* form to the typical *stelliformis*, the latter being the larger. The dozen or so specimens previously in the museum fit into their places in this series. There can therefore be no doubt that the alleged species or variety *O. campanulatus* is merely the young of *O. stelliformis*.

Apart from mere size the growth-changes consist in:

1. An increase in the greatest diameter as compared with the height of the theca.

2. The lowering of the ambitus from a position but little below the oral pole to one less than half the height of the theca from the base.

3. A consequent change from a tumbler outline, through a bell outline, to a parachute outline, the sides changing from straight, or in part convex, to concave, and the summit changing from almost flat to flattened-convex or convex.

4. With the extension of the ambulacra in length, the radials grow outward, and the cross section at the ambitus becomes more stellate.

5. Concurrently the number of ambulacrals (side-plates, etc.) increases.

6. A change in the outline of the ambulacra outside the deltoids from broadly lanceolate, through narrowly lanceolate, to the characteristic outline of the adult, which is broad in the proximal region, then rather rapidly tapering to a region from one-third to two-thirds the distance from the proximal end, then narrow and gently tapering.

7. The distal region of the ambulacrum is in all stages depressed below the edges of the radial sinus, but the proximal region, which in the young is flush with the sinus, gradually rises above it, until in the largest individuals it projects conspicuously; and this projecting portion increases in length, until it nearly (though never quite) attains the distal lip of the sinus.

8. Concomitantly with the preceding change, the edges of the sinus become sharply beveled, and the two beveled faces of adjacent limbs of the radials meet in a ridge on the deltoid.

9. The curve of the side of the theca below the ambitus, though described above as straight or concave, is never a simple curve, but consists of three parts: (*a*) the almost vertical sides of the basal circlet, (*b*) the outwardly spreading lower part of the radials, which is straight or feebly convex, (*c*) the part of the radials below the lip, which in the young bends outward almost imperceptibly, but gradually lies at a sharper angle to region *b*, until it is at last horizontal.

10. The distal parts of the radial above this region *c* come to be marked off from the body of the radial by a vertical depression, which at its upper end meets the distal end of the beveled surface mentioned under (8).

11. Various changes of proportion in details are scarcely worth setting out, since all follow from the one great change, namely the extension of the ambulacra outward, arching upward, and bending downward, unaccompanied by equally rapid growth of the other elements.

It follows from the preceding that such a description as that given by Etheridge & Carpenter for *O. stelliformis* could not apply even to all the forms which they themselves labeled with that name. Some of the necessary modifications will be gathered from what has been said. There are other variations which may be mentioned.

The deltoids are said to be constricted at one-third of their length from the proximal end. In the large E 30091 the measurements are 4.6/8.4 mm., i.e., more than one-half. In the medium-sized E 30099 they are 1.8/3.8 mm., i.e., rather less than one-half. In the smallest E 30106 they are 1.1/1.9 mm.

The anal deltoid is said to have its distal margin rounded. This seems to be the case in the two specimens from Burlington registered E 841, as also in E 30096; but in most of the specimens the sutures are straight, and, even when curved, nearly always meet in a decided angle.

The number of side-plates on each side of an ambulacrum is given as fifty, on the authority of Meek & Worthen. It did not reach this number in any of the specimens before Etheridge & Carpenter. In E 1055 the total is thirty-five or less. In those registered E 840, the total is forty or less, and in one case twenty or less. In E 8172*a*, it is about twenty-five; and in E 8172*b*, about forty. In the very young E 30106 from White Ledge, the number is about nine. From this it increases to fifty in E 30093, sixty in E 30092, and something over sixty in E 30091. In E 842*b*, referred to var. *campanulatus* by Etheridge & Carpenter, the number is thirteen or fourteen, and was probably the same in E 482*a*. In all individuals the number of side-plates to 3 mm. is nine or a fraction more.

The ornament, when preserved, as in E 30094, consists, on the radials, of the usual growth-lines; these also occur on the upper part of the basals, but on their lower part, where the basals form a cylinder, the lines are coarse, irregular, and rugose.

The cover-plates pass right up to the oral pole in E 30099, apparently without fusion or enlargement. Since no one has ever doubted that they could open on the ambulacra, there is no reason why precisely similar plates should not have opened over the mouth. Possibly these plates may have fused over the mouth in some

individuals, as supposed by C. A. White, Meek & Worthen, and Etheridge & Carpenter. In E 30106 they are not preserved, but the notches indicating a mobile articulation extend round the peristone; in so young a form one would not expect these plates to have been fused.

The new material shows no traces of plates covering the anal aperture, or of facets for plates of a tube raised above it as suggested by Etheridge & Carpenter.

The horizon of all specimens in the British Museum is given as Lower Burlington. I do not find either the species or its supposed variety recorded from any other horizon. It would, however, be interesting to work out its vertical distribution with more accuracy, and to see whether the earlier representatives are closer to the tumbler or bell-form of the smaller, and supposed younger, individuals in our series; and whether the later representatives are closer to the parachute-form of the larger, and supposed older, individuals.

POSSIBLE SILURIAN TILLITE IN SOUTHEASTERN BRITISH COLUMBIA

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From the eastern slopes of the Purcell Range, in the vicinity of Lake Windermere, the view across the deep depression known as the Rocky Mountain trench to the Rocky Mountains on the east, shows a series of bands of rocks varying in color and running roughly parallel to the trench. One of these is a red conglomerate, which can be traced almost uninterruptedly for ten miles between the Sinclair River and Shuswap Creek, both of which are tributary to the Columbia River in the Rocky Mountain trench. The red formation was examined in two localities, and in a third a yellow conglomerate was found, which is undoubtedly a part of the same formation. In the last instance evidence was found which points toward a glacial origin of the conglomerate.

The conglomerate was first studied at Sinclair Springs. Here an outcrop of red rock, with a dip of about 90°, forms a high wall running down one side of the canyon and up the other (Fig. 1). Closer examination shows that the rock is not made up entirely of red material, but consists of bowlders, which are predominantly red, imbedded in a yellow calcareous matrix. The bowlders are limestone with the exception of a very few pieces of quartzite. The limestone varies considerably, having such varieties as purple, black, white crystalline, blue with white veins, and gray. The bowlders are mostly sub-angular and in some cases are as large as four feet in diameter (Fig. 2). The material of the conglomerate is unassorted, and shows no trace of stratification. Two bowlders were seen which had polished surfaces. It was difficult to remove the bowlders from the matrix, and the exposed surfaces of the bowlders were so weathered that any striations they may have once possessed have been destroyed.

The thickness of the conglomerate is about 200 feet. Against it on the east, with apparent conformity, is gray limestone. This contains a scattering of pebbles in the portion next the conglomerate. Six hundred and fifty feet below the top of the limestone is a bed containing fossils of Richmond age. As these beds are vertical, the age relations of the conglomerate to the limestone are not shown by the structure, but since somewhat older Ordovician faunas

Fig. 1.—The red conglomerate near the Sinclair Hot Springs

occur farther east, the conglomerate is known to be 650 feet above strata containing the Richmond fauna. Above the bowlder bed there is a break in the succession, and above the break is massive crystalline limestone in which no fossils were found. Farther west there is severe faulting which cuts out further evidence from fossils on that side. From the evidence on the east it was concluded that the age of the formation probably is Silurian because of the 650 feet of limestone between it and the fossil bed which represents the top of the Ordovician.

Two miles up the canyon of Shuswap Creek the southward continuation of the formation was examined and found to be practically identical with that seen at Sinclair Springs. The bowlders are not so large on the average, but are equally angular and unrounded. In two places there are thin lenses of crumpled strata included in the formation. Both of these were only a few inches thick and did not extend more than 4 or 5 feet before being cut off by bowlders. The formation here is 150 feet thick. To the west there is crystalline limestone very similar to that found on the

FIG. 2.—A typical section of the conglomerate. The hammer illustrates the size of the bowlders.

same side at Sinclair Springs. On the east there is a thin bed of quartzite, followed by massive limestone. To the south, up Windermere Creek in the vicinity of the Blue Lakes, there is conglomerate in direct line with the red bowlder bed. Here the character of the bowlders is quite different, as are also the distribution of the outcrops and the type of weathering, but there is sufficient evidence to show that the two conglomerates are parts of one formation.

The formation in Windermere Creek valley is probably 400 or 500 feet thick and extends along the north side of the canyon for at least three-quarters of a mile. It is in the form of an anticline plunging to the south, and disappears in that direction.

The bowlder bed here consists of a firmly cemented aggregation of limestone, quartzite, and shale blocks with a few fragments of igneous rocks. Limestone is the most abundant constituent, but in some places quartzite bowlders predominate. Many of the pebbles and bowlders are distinctly faceted. Many of them are polished and some rounded as if by stream action. In some cases the quartzite surfaces are so polished as to be dazzling in the sunlight. Markings which suggest glacial striations were found on at least one bowlder. A large block of quartzite was seen to have on its surface a distinct gouge about ten inches long, three inches wide, and half an inch deep. A number of quartzite pebbles had concave surfaces. Evidence from fossils in the bowlders indicates the age of the conglomerate to be younger than Richmond.

The contact of the bowlder bed with the underlying calcareous shale is distinctly seen. The topmost layer of the shale is contorted and contains pebbles ranging up to six inches in diameter. They undoubtedly came from the same source as the overlying conglomerate and indicate that the shale was soft when the conglomerate was deposited.

The bowlder bed is overlaid to the west by massive limestone, with a slight gradation between the two. It is difficult to find the contact because it is covered by débris in most places.

Before considering the evidence that the formation is tillite, other possible modes of origin may be considered. Is the conglomerate in question (1) a stream conglomerate, (2) an autoclastic breccia, or (3) an undercliff breccia? The size and sub-angularity of the bowlders are difficult to explain if the conglomerate is fluviatile. Such bowlders are commonly found only in the valleys of mountain streams. As there is no evidence for a change in dip between the underlying and overlying limestone at Sinclair Springs, it is very improbable that there was any intervening uplift which could have led to the development of mountain streams. Further, the gradation between the bowlder bed and the limestone shows that the conglomerate could not have been deposited by mountain torrents.

Autoclastic breccias are more or less local phenomena. They are generally not confined to one stratigraphic horizon, but are

likely to cross bedding planes, while the formation in question constitutes a distinct horizon traceable for a number of miles. The diversity of types of rock among the bowlders in the Windermere Creek occurrence is not characteristic of an autoclastic breccia, and the thickness of the formation is also against this interpretation.

Undercliff breccias have angular unsorted material such as found in this formation, but the possibility of adjacent cliffs at this time is slight, because of the gradation into overlying and underlying limestone, which shows only slight interruption of marine conditions. The great continuation of the formation both along the range and in a vertical direction (it has a known vertical range of more than 3,000 feet) are altogether against a cliff-base origin.

On the other hand, evidence for glacial action is strong. It includes (1) the finding of probable striations, (2) the sub-angularity of the bowlders, (3) the distinct faceting of some of the bowlders, (4) the heterogeneous mixture of the bowlders without assortment or stratification, (5) the occurrence of grooving and concave faces on pebbles, and (6) the occurrence of Silurian tillite in southeastern Alaska,[1] 900 miles away, also is significant.

Thus it seems possible that glacier ice existed at this period in British Columbia and southeastern Alaska. Since there are marine deposits on both sides of the formations in Alaska as well as in British Columbia, it is possible that the glaciers came out into shallow seas in these places. The absence of weathering at the top of the conglomerate points to encroachment of the sea before such weathering took place. The gradation into limestone in several instances in British Columbia suggests that icebergs coming from the retreating or advancing ice fronts distributed occasional bowlders among the limestone deposits. It is not surprising that this formation should continue over such great distance without a break, when it is considered that sea deposits covered it before it could be attacked by erosion.

[1] E. Kirk, *Amer. Jour. Sci.*, Fourth Series, September, 1918, p. 511.

REVIEWS

Source Book for the Economic Geography of North America. By CHARLES C. COLBY. The University of Chicago Press. 1921.

Even a brief study of this volume shows that it will serve a good purpose, for it is a step—and an important one—in the organization of material which is scattered so widely that its utilization is out of the question for those not in touch with good libraries, and sometimes discouraging to those who are. Every student of college grade who studies the geography of North America will find the book of great service, if not indispensable. The teacher of such students should welcome the volume, not as a textbook, but as the basis for a course on the economic geography of the continent. He must not expect that the book is to do away with his own work, but he may expect it to give him many suggestions as to methods of procedure and as to sources of material. Intelligent use of the book will make it serviceable for courses of various grades of advancement, and even for courses with somewhat diverse aims. A good feature of the book is that it gives publicity to much excellent material published in government reports and largely lost to view by many who could utilize it to advantage.

One cannot help wishing that the book were somewhat fuller, and that a well-annotated bibliography had been added. This may come with future editions.

R. D. S.

The Malagash Salt Deposit, Cumberland County, Nova Scotia. By A. O. HAYES. Ottawa: Canadian Geological Survey, Memoir 121, 1920. Pp. 24, fig. 1, maps 2.

Mining development has proved the presence of a sufficient quantity of pure salt in this area for the establishment of an important industry. The deposit is favorably located with respect to the supply of raw material and fuel, and has exceptional advantages for transportation either by rail or water.

Outcrops are not very abundant in the area, but sediments belonging to the Mississippian, early Pennsylvanian, and late Pennsylvanian or early Permian are identified, and are separated by two marked uncon-

formities. The Mississippian is represented by the Windsor series and the salt is interbedded with gypsum and shale in this series. The Windsor series has been intensely folded and faulted and is now exposed on the crest of an anticline where the main workings are located. The salt bed is about 75 feet below the surface. A shaft has been sunk to the salt horizon and the salt is removed by mining. One bed of rock salt over 21 feet thick is already being worked. Sylvite (potassium chloride) is present as fairly pure lenses in the halite and probably is a replacement of halite. Chemical analyses of rock salt show from 2.5 per cent to 11 per cent sylvite, and this potassium salt will probably be an important by-product from this deposit. Very little is known concerning the lateral extent of these salt beds, but since they were formed by the evaporation of sea water during the recession of the Mississippian seas in Windsor time, they are likely quite extensive.

The Windsor series is probably much more extensive than formerly thought, because limestone in Kings County, New Brunswick, formerly correlated with the Albert series, which is unconformable below the Windsor series, was found to contain Windsor fossils. A number of salt springs occur in the area where these fossils were collected and in other localities in New Brunswick and suggest the presence of salt beds in the Windsor series of this province, although up to the present no development work has been done near any of the springs.

J. F. W.

The Limestone and Phosphate Resources of New Zealand. Part I. Limestone. By P. G. MORGAN. Geological Survey Branch, Department of Mines, New Zealand, 1919.

This is primarily a discussion in detail of the limestone resources of New Zealand, considered particularly in their relation to agriculture, and as such is mainly of local interest. The principal features of general interest are several excellent plates that illustrate remarkable fluted and pinnacled forms developed through erosion by solution.

As bearing upon the origin of oölitic and pisolitic structures in limestone, relations at Kotuku near Greymouth are of interest. Here several drill holes, sunk in search of oil, discharge in geyser-like fashion salt water highly charged with CO_2 and dissolved calcium carbonate. The greater part of the CO_2 at once escapes and, in consequence, abundant carbonate of lime is deposited wherever the water touches any solid object. As the water flows away it forms numerous little balls of carbonate of lime, in size and shape resembling marbles.

E. S. B.

Maps and Sections to Accompany Report on the Geology and Ore-Deposits of Meekatharra, Murchison Goldfield. Geological Survey of Western Australia, Bulletin No. 68, 1916. Pls. I–XXV.

The bed rock of the area consists chiefly of amphibolite and other varieties of schists, into which numerous granitic masses have been intruded. There are also present some extrusives and a few local occurrences of Devonian shales, arkoses, and dolomites. The bulletin consists of numerous geologic maps and sections, and mine maps for the area.

A. C. McF.

Maps and Sections to Accompany Report on the Geology and Mineral Resources of the Yilgarn Goldfield. Geological Survey of Western Australia, Bulletin No. 1, Pt. III, 1917. Pls. I–XIX.

The geology as shown on the maps and sections is essentially the same as found in the other gold fields of Western Australia, consisting chiefly of igneous and metamorphic rocks and a minor amount of sedimentary. The report includes detailed maps to the scale of one mile to the inch, as well as more generalized maps on a much smaller scale.

A. C. McF.

The Cambrian and Ordovician of Maryland. By R. S. Bassler. Systematic Report, Maryland Geological Survey, 1919. Pp. 424, pls. 58, figs. 27.

The Ordovician and Cambrian are considered together because of the continuity of the limestone which forms the top of the one and the base of the other. The proposed Ozarkian and Canadian systems are not recognized. Three great phases of sedimentation are recognized, (1) the Lower Cambrian siliceous phase, (2) the great limestone deposits of the Upper Cambrian and Lower Ordovician, and (3) a shale phase covering the Middle and Upper Ordovician, the three forming an aggregate about 16,000 feet thick, of which the limestones form more than half. The first phase mentioned is more or less confined to the Blue Ridge, the limestones to the Great Valley and Allegheny Ranges, and the shale phase chiefly to the latter.

The description of formations includes detailed sections, faunal lists, discussion of correlations, topographic features, areal distribution, and economic resources. In many of them distinct faunal zones are recognized. There is appended a general faunal list showing the geographic distribution of the forms.

The part devoted to systematic paleontology contains the description of some two hundred species and varieties, of which sixteen are new. Most of these are figured on the fifty-eight plates. There is also a bibliography of Cambro-Ordovician literature.

A. C. McF.

Contributions to the Pre-Cambrian Geology of Northern Michigan and Wisconsin. By R. C. Allen and L. P. Barrett. *The Geology of Limestone Mountain and Sherman Hill in Houghton County, Michigan.* By E. C. Case and W. I. Robinson. Michigan Geological and Biological Survey, Publication 18, Geological Series 15, 1915. Pp. 189, pls. 12, figs. 15.

Part I consists of a number of contributions on the geology of an area lying west of the Crystal Falls and Iron River districts, and extending south of the Marquette and Gogebic iron ranges to the state line and into Wisconsin beyond. The region is a great Huronian interior in which the better-known and structually distinct ranges on its north and east borders coalesce and lose their identity. The authors are unable to say that rocks older than the Huronian are present, but find that the area heretofore mapped as Archaean and undifferentiated pre-Cambrian is in reality Huronian. The outstanding feature of the region is the presence of an enormous granite mass intruded into the Lower and Middle Huronian sediments, constituting a great batholith which seems to occupy many thousands of square miles in northern Wisconsin, and is represented by outlying remnants in the east end of the Gogebic range and southwest and east in Michigan. The contributions consist of the descriptions of the geology of a number of districts and ranges, together with discussions and some revisions of the correlations of the pre-Cambrian rocks of the region.

An important conclusion arrived at by the authors is that the formations heretofore included in the Upper Huronian are separable into two groups by an unconformity of the first magnitude. For the upper one of the two the name Copps is proposed.

Part II: Limestone Mountain and Sherman Hill are outliers of Paleozoic dolomite found in Houghton County. The stratigraphic range is from the Cambrian to the Middle Devonian, including the Cambrian Upper Black River, Decorah, Upper Galena, Richmond, Niagaran, and Middle Devonian. Belief in the presence of the Devonian is based on a piece of float found on the hillside. The structure has

been worked out in detail and includes numerous minor faults. The great importance of the work lies in the establishing of the Ordovician, Silurian, and Devonian seas in the region. The similarity of the Ordovician fauna of this region with that of Minnesota and Wisconsin indicates they were all part of the same invasion. Good faunal lists are given.

A. C. McF.

Maps and Sections to Accompany Report on Contributions to the Study of the Geology and Ore Deposits of Kalgoorlie, East Coolgardie Goldfield. Perth: Geological Survey of Western Australia, Bulletin 69, Part III, 1917.

The gold deposits at Kalgoorlie, Australia, are of two types, the gold-quartz veins and the gold-telluride deposits. The bed rock of the region outside of some minor metamorphosed sediments consists of granite and amphibolite schists. It is with the last-named that the gold is usually found. *Bulletin 69* consists of fourteen plates showing the areal and structural geology of the region.

A. C. McF.

Eleventh Biennial Report of the State Geologist on the Mineral Industries and Geology of Vermont. By GEORGE H. PERKINS, *et al.* Burlington, 1917–18. Pp. 209, pls. 18, figs. 10.

The present report consists of a number of contributions by different authors on the geology of the state of Vermont. These are as follows:

I. "Physiography of Vermont," by G. H. PERKINS.—The discussion and description of the physiography is given in a popular though thorough style. The physiographic history, which is rather complex, is well summarized. The mountain areas include regions of complex igneous and metamorphic history. Most of the large rivers are old and antecedent in character. The author believes that most of the lakes of the state are glacial in origin.

II. "The Ordovician Terranes of Central Vermont," by CHARLES H. RICHARDSON.—The formations discussed are all pre-Trenton in age and include, from base upward, the Irasburg conglomerate, the Memphremagog slates, and Waits River limestone. A brief summary of the geologic history of the state is given.

III. Post-Glacial Sea-Level Waters in Eastern Vermont," by H. L. FAIRCHILD.—Mr. Fairchild describes the post-glacial marine features found in the eastern part of the state, thus supplementing an earlier

article dealing with the western portion of the state. With regard to the crustal movements which such features involve, he states:

"The earth's superficial or crustal portion is sensitive to unequal loading, or differential pressures, and it appears that northeastern North America was depressed by the weight of the long persistent ice sheets of the recent glacial time. With the removal of the weight by the melting of the ice body, the land rose. The amount of Post-Glacial land uplift, and the area affected seem to have been proportionate to the calculated thickness and extent of the latest ice sheet."

The article is accompanied by a map representing the approximate amount of post-Glacial uplift as shown by isobases.

IV. "A Report of the Geological Work within the Rochester Vermont Quadrangle," by W. G. Foye.—Rochester quadrangle lies within the heart of the Green Mountains, midway between the Champlain and Connecticut valleys. The structure is rather complex, with the bed rock chiefly pre-Cambrian.

V. "The Terranes of Northfield, Vermont," by Charles H. Richardson and Samuel H. Camp.—The geology of Northfield is intricate. The terranes consist of a series of highly crumpled, folded, and faulted metamorphic rocks, dipping at high angles and cut by intrusive masses. The discovery of Ordovician fossils in the Northfield slate quarries and in the limestone and quartzose marbles, has made possible the accurate stratigraphic correlation of these beds and constitutes the most important result of the work.

VI. "The Terranes of Roxbury, Vermont," by Charles H. Richardson.—The work here was very similar to that at Northfield, important graptolite faunas being found forming the basis for the correlation of the beds of the area. The origin of the verd-antique marble, which is of commercial importance, is carefully studied.

XI. "Eruptive Rocks at Cuttingsville, Vermont," by J. W. Eggleston.—The general character of the main body of the igneous rock mass indicates that it is a composite stock. The order of eruption found was from the more basic essexite through the syenites to the more acid nordmarkite. In the complementary dikes the order was reversed, tinguaite dikes antedating the camptonite dikes.

Other chapters are: VII. "Progress in Copper Mining and Milling," by E. C. Jacobs; VIII. "Progress in Talc Production," by E. C. Jacobs; IX. "The Lime Industry in Vermont," by E. C. Jacobs; X. "Additional Corrections to the List of Altitudes in Vermont," XII. "Provisional Report of the Areal and Structural Geology of the West Flank of the Green Mountain Range," by N. C. Dale; XIII.

"The State Cabinet;" XIV. "Mineral Resources"; XV. "Progress of Stream-Gaging in Vermont during the Two-Year Period Ending September 30, 1918"; XVI. "Records of Stream Flow for the Two-Year Period Ending September 30, 1918," by the United States Geological Survey in co-operation with the State Survey.

It may be noted that Vermont led in talc production in 1917, the grade of talc, however, being low. In the production of granite and marble it leads, and in slate it is second only to Pennsylvania.

A. C. McF.

An Annotated Index of Minerals of Economic Value, to Accompany a Bibliography of Indian Geology and Physical Geography. Compiled by T. H. D. la Touche, M.A., F.G.S., Fellow of the Asiatic Society of Bengal. Calcutta: Geological Survey of India, 1918. Pp. 490.

The purpose of the author is to furnish a guide to the literature on Indian minerals of economic importance and at the same time to indicate as concisely as possible the nature of the information given by each of the various writers. These notes (Part II) are supposed to be used in conjunction with the bibliography which forms Part I of the work. The minerals are arranged alphabetically, or frequently under group heads where they are chemically or economically related to one another.

A. C. McF.

The Geology of the Tuapeka District, Central Otago Division. By P. Marshall, M.A., D.Sc., F.G.S. New Zealand Department of Mines, Geological Survey Branch, Bulletin No. 19 (N.S.). Pp. 72, pls. 12.

This report consists of a description of the general geology and physiography of the region, together with its various cultural and natural features. The formations present include the pre-Jurassic Tuapeka series, which, so far as now known, may be of any age between pre-Cambrian and Jurassic, and the Waitahuna series of Upper Cretaceous and Lower Eocene age, together with some Pleistocene and Recent deposits. The Tuapeka series represents deposits of littoral sands and muds and the Waitahuna true marine sediments, with some associated volcanics.

The chief economic resource of the region is gold, which occurs disseminated in conglomerate beds or as lodes. It is believed to be primary in the conglomerate. Other minor mineral resources include antimony, copper, cinnabar, and scheelite.

A. C. McF.

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

A New Occurrence of Crystobalite in California. By AUSTIN F. ROGERS.

Fault Features of Salton Basin, California. By JOHN S. BROWN.

A Criticism of the "Faunal Relationships of the Meganos Group," by Bruce L. Clark. By ROY E. DICKERSON.

Former Courses of the Androscoggin River. By IRVING B. CROSBY.

Notes on the Sand Dunes of Northwestern Indiana. By GEORGE B. CRESSEY.

Marine Upper Cretaceous and a New Echinocorys from the Altaplanicie of Bolivia. EDWARD W. BERRY.

Post-glacial Lakes in the Mackenzie River Basin, Northwest Territories, Canada. By A. E. CAMERON.

The Occurrence of an Apus in the Permian of Oklahoma. By RUDOLF RUEDEMANN.

On Contact Phenomena between Gneiss and Limestone in Western Massachusettes. By PENTTI ESKOLA.

The Early Pre-Cambrian Formations of Northern Ontario and Northern Manitoba. By E. L. BRUCE.

The Reaction Principle in Petrogenesis. By N. L. BOWEN.

An Outline of the Physiographic History of Northeastern Ontario. By W. H. COLLINS.

Dinosaur Tracks in Hamilton County, Texas. By W. E. WRATHER.

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February-March 1922

THE GREAT FAULT TROUGHS OF THE ANTILLES[1]

STEPHEN TABER
University of South Carolina, Columbia, S. C.

INTRODUCTION

The region of the Greater Antilles is characterized by a marked elongation of the principal geographic features in an east-west direction and by extremely high relief (Plate I). The highest point above sea-level, Mount Tina on the island of Haiti, has an elevation of over 3,100 m. while the deepest sounding in the Atlantic Ocean (8,526 m.) was obtained only 320 km. to the northeast.[2] The Antillean mountain ranges are among the most precipitous in the world, but their slopes are, in large part, submerged beneath the surface of the Atlantic Ocean and Caribbean Sea. Off the north coast of St. Croix the descent is 4,348 m. in a distance of 8 km., and for shorter distances the slopes are very much steeper.

The physiography of the Greater Antilles is very complex and as yet little of the region has been studied in detail. The dominant tectonic trend is approximately east and west along arcs convex toward the north, in part following the margins of the great trough-like depressions which are such a striking characteristic of the

[1] Presented in part at the Chicago meeting of the Geological Society of America, December, 1920.

[2] All elevations and soundings have been taken from the maps of the Hydrographic Office of the United States Navy.

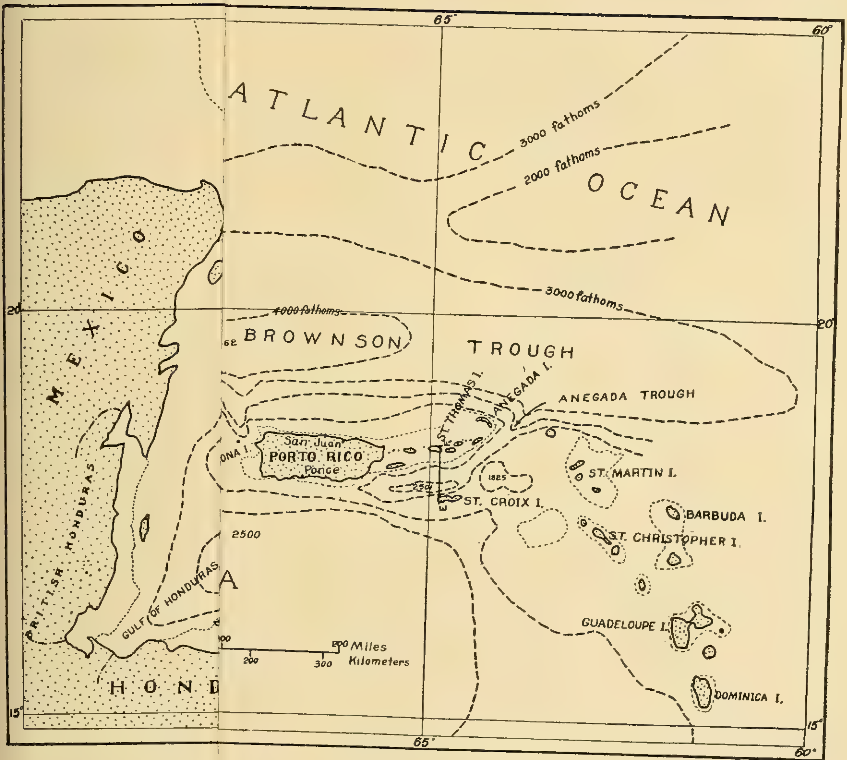
region. These arcs cut directly across the earlier tectonic lines and are everywhere marked by extremely precipitous slopes.

The evidence outlined in the following pages indicates (1) that the east-west arcs delineating the major relief features of the Greater Antilles are zones of normal faulting developed in late geologic time; (2) that this faulting has resulted in the formation of the great troughs of the region; and (3) that the displacements are continuing at the present time.

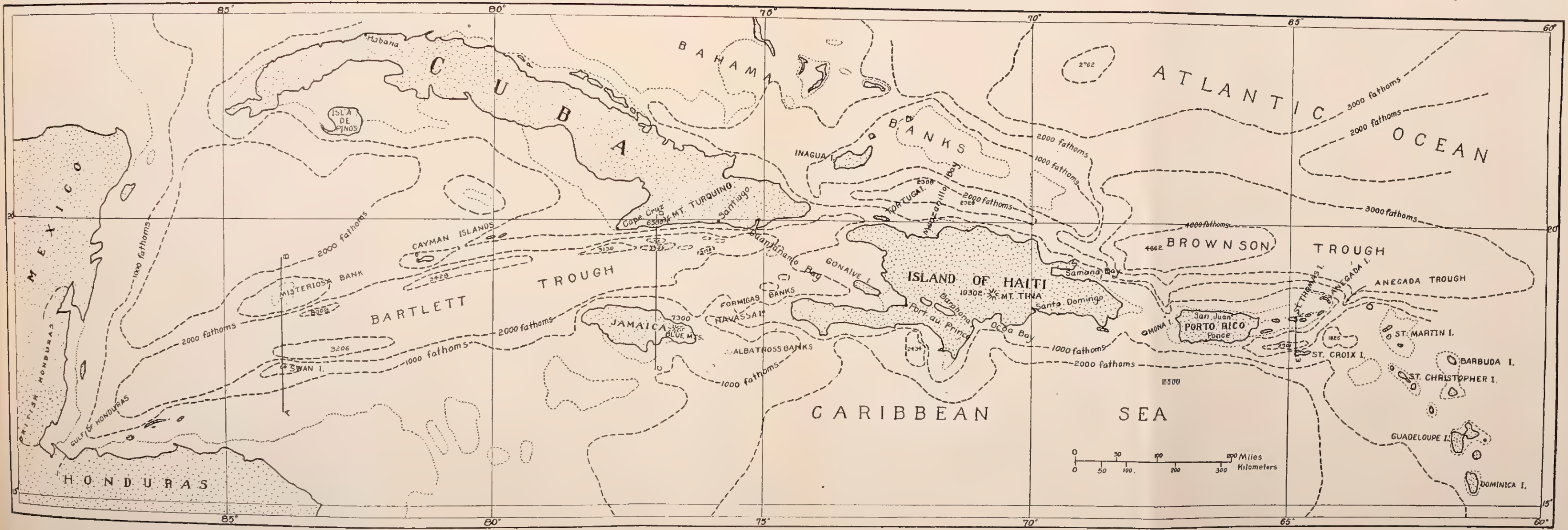
CRITERIA OF FAULTING

The fault-zone hypothesis rests partly on geologic evidence, but largely, since most of the region is under water, on evidence that is either topographic or seismologic. Topographic evidence of faulting is unusually well preserved because the fault scarps are mostly below sea-level where they have been protected from erosion. The characteristics of these scarps which indicate an origin through faulting are (1) great height; (2) extremely precipitous slopes; (3) abrupt changes in slope at top and bottom; (4) rectilinear course for long distances; and (5) subordinate depressions and elevations (troughs and horsts) near the base of the main scarps.

The last-mentioned features develop within fault zones as a result of the differential displacement of long narrow blocks or wedges formed by the branching and intersection of nearly parallel faults. The formation of these subordinate troughs and horsts is a common accompaniment of normal faulting on a large scale and especially of trough faulting. On land these minor topographic effects of faulting are soon obliterated by erosion and by the accumulation of rock-waste in the troughs; therefore the significance of these criteria in the recognition and interpretation of faulting has been generally overlooked. Because of their short life these topographic features are seldom found on land except in arid regions and where very recent displacements have occurred along old fault zones. Beautiful examples of this type of fault topography on a small scale have developed along the Wasatch fault zone in Utah as a result of post-Pleistocene displacements. Similar topographic effects were produced in California by the faulting that accompanied



ATLANTIC OCEAN
3000 fathoms
2000 fathoms
3000 fathoms
4000 fathoms
BROWNSON TROUGH
ANEGADA TROUGH
ANEGADA I.
ST. THOMAS I.
MEXICO
BRITISH HONDURAS
GULF OF HONDURAS
HOND
San Juan
PORTO RICO
Ponce
ONA I.
ST. CROIX I.
ST. MARTIN I.
BARBUDA I.
ST. CHRISTOPHER I.
GUADELOUPE I.
DOMINICA I.
2500
1825
Miles
Kilometers
200
300
65°
60°
20°
15°



Map of the Greater Antilles, Showing Fault Troughs

Contour interval, 1,000 fathoms (6,000 feet). Areas within the dotted lines, less than 100 fathoms.

the Owens Valley earthquake of 1872;[1] and there are many examples along the line of the San Andreas fault zone of California.

Seismologic evidence, when available, is especially valuable in locating active faults which are not exposed to direct observation. Many earthquakes have been recorded in the Greater Antilles and Virgin Islands during the last four centuries, and, while the published catalogues of these earthquakes are far from complete, it seems probable that few, if any, of the very destructive shocks have been omitted. Most of the weak shocks of a district originate in the same localities as the stronger ones, and therefore in this investigation attention has been focused on the destructive earthquakes. In the region of the Greater Antilles the epicenters of destructive earthquakes, instead of being scattered at random, are almost entirely limited to a few well-defined belts, which also possess the topographic characteristics of fault zones.

Most of the earthquakes occurred before seismographs were developed, and, therefore, in determining the location of their epicenters, it has been necessary to rely chiefly on the distribution of intensities and the evidence derived from a study of accompanying sea waves. Fortunately, for present purposes an approximate location of an epicenter is, in most cases, sufficient. The seismologic data are only briefly summarized here as they are discussed in more detail in another paper which will be published shortly in the *Bulletin of the Seismological Society of America.*

DESCRIPTION OF FAULT ZONES AND FAULT TROUGHS

The principal troughs of the Antillean region are: the Bartlett Trough, which lies between Cuba and Jamaica and extends from the Island of Haiti westward into the Gulf of Honduras; the Brownson Trough, lying immediately north of Porto Rico and the Virgin Islands; and the Anegada Trough, which separates Porto Rico and the Virgin Islands Bank from St. Croix and the Lesser Antilles. In addition to these there are some minor troughs and probably one fault zone that is not associated with any trough.

[1] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Surv. Monograph I* (1890), p. 361.

THE BARTLETT TROUGH[1]

The Bartlett Trough is probably the most striking physiographic feature of the Antillean region (Fig. 1). It is a long, narrow trench stretching from the Gulf of Honduras eastward into Gonaïve Gulf between the two western peninsulas of Haiti, a distance of 15° or 1,570 km. Its width, where widest, between Cuba and Jamaica and near the Cayman Islands is 150 to 160 km. Its deepest sounding, 3,506 fathoms (6,412 m.) was obtained less than 50 km. from the coast of Cuba and is over 8,275 m. below the higher peaks of the Blue Mountains in Jamaica and the Sierra Maestra in southern Cuba. The six deepest places (all over 3,000 fathoms) are close to the inclosing scarps rather than near the center of the trough. The floor of the trough seems to be relatively flat over quite large areas, but in longitudinal profile rises and falls throughout its length. The Bartlett Trough lies between two great fault zones which may be traced longitudinally far beyond the limits of the trough itself. They are here designated the Swan Island–Jamaica–South Haiti fault zone and the Cayman Islands–Sierra Maestra–North Haiti fault zone.

Swan Island–Jamaica–South Haiti Fault Zone.—This fault zone may be traced westward from its juncture with the northern escarpment of the Caribbean Basin in the vicinity of Ocoa Bay, Santo Domingo, across Haiti, and along the southern side of the great Bartlett Trough. On the Island of Haiti it is marked by a trough-shaped valley 15 to 20 km. in width, which extends from Barahona on Neyba Bay to Port-au-Prince, a distance of about 150 km. Throughout its length this depression is confined between the precipitous fronts of two lofty mountain ranges. The floor of the trough comprises the plain of the Cul de Sac in the west, the plains of Neyba in the east, and the lake region lying between. Two of the lakes contain salt water, and W. F. Jones states that they are both below sea-level, but at different elevations.[2] A very slight subsidence of the land would com-

[1] A brief description of this trough was given in a previous paper, "Jamaica Earthquakes and the Bartlett Trough," *Bull. Seis. Soc. of Amer.*, Vol. X (1920), pp. 84–88.

[2] W. F. Jones, "A Geological Reconnaissance in Haiti, A Contribution to Antillean Geology," *Jour. Geol.*, Vol. XXVI (1918), p. 730.

pletely submerge the floor of the trough and separate the Tiburon Peninsula from the rest of Haiti.

The depression has been described and figured by Jones as a normally faulted block, buried under Quaternary deposits which have been removed at one place exposing highly tilted Oligocene-Miocene sediments. Limestones of Eocene–Early Oliogcene age are exposed along the flanks of the inclosing ranges while late Tertiary intrusives form the core of the mountains on the south. Another "large fault is indicated well up on the south range of Haiti, a well-marked depression extending east and west along the course of this fault."[1]

Along the north side of the salt lakes Jones found basalt-flows, which he thinks came from fissure eruptions; and he states that between the Cul-de-Sac depression and Ville Bonheur (Saut d' Eau) there is a well-defined crater from which extend basalt-flows, so recent in origin that they have not been appreciably modified by erosion.[2] In the Province of Azua, Santo Domingo, there are rocks of igneous origin, which C. W. Cooke states are not older than Pleistocene.[3]

During historic times the fault trough of southern Haiti has been the locus of more earthquakes of high intensity than any similar area in the Greater Antilles. The high seismicity of this depression is noted by Scherer in his excellent article on "Great Earthquakes in the Island of Haiti"[4] from which most of the data on Haitian earthquakes given in this paper have been abstracted.

The cities of Azua and Santo Domingo, located on alluvial ground a short distance north of the fault zone and near its juncture with the Caribbean escarpment, have been damaged repeatedly by earthquakes. They suffered from severe shocks in 1673, 1684, and 1691, Azua being entirely destroyed in 1691. On October 18, 1751, an earthquake threw down all houses in Azua and a sea-wave overwhelmed the town. It was rebuilt farther inland.

[1] *Ibid.*, p. 751. [2] *Ibid.*, pp. 750–51.

[3] C. W. Cooke, "Geological Reconnaissance in Santo Domingo," *Bull. Geol. Soc. Amer.*, Vol. XXXI (1920), p. 218.

[4] Rev. J. Scherer, "Great Earthquakes in the Island of Haiti," *Bull. Seis. Soc. Amer.*, Vol. II (1912), pp. 161–80.

Other towns near the coast were severely damaged, Santo Domingo City losing many of its finest buildings. The earthquake of 1751 and several other shocks, assigned by Scherer to the central valley of Haiti, are here correlated with the southern fault trough because of high intensities near the coast and the phenomena of the sea-wave. The earthquake of May 11, 1910, cracked walls in Azua and Santo Domingo City. Scherer states that "the strongest part of the earthquake occurred in the Bay of Ocoa where the sea-wall was broken."[1]

The fault trough apparently continues westward into the Gulf of Gonaïve, for there is a marked depression between Gonaïve Island and the straight north coast of the Tiburon Peninsula. The earthquake of November 9, 1701, threw down masonry houses on the plains near the western end of the trough, and the road along the north shore of the Tiburon Peninsula from Léogâne to Petit Goâve sank into the sea. The severe earthquakes of November 21 and 22, 1751, destroyed the recently founded town of Port-au-Prince and overthrew buildings on the plain of the Cul de Sac. Lyell states that "part of the coast 20 leagues in length sank down and has ever since formed a bay of the sea,"[2] but the writer has found nothing which would confirm this assertion.

The earthquake of June 3, 1770, was one of the strongest shocks recorded on the Island of Haiti, the area of greatest destruction extending from Croix de Boquets through the plain of the Cul de Sac to Port-au-Prince and along the north coast of the Tiburon Peninsula as far as Miragoâne. Southey states that "the sea rose a league and a half up into the island"[3] but does not mention where this occurred. Scherer states that at Grand Goâve the foot of the mountain of La Saline was partly submerged and at Arcahaie north of Port-au-Prince, a wave was also recorded.[4]

The earthquake on the night of April 8, 1860, originated a little farther west than the disturbances previously described, the inten-

[1] Rev. J. Scherer, *op. cit.*, p. 172.

[2] Sir Charles Lyell, *Principles of Geology*, Vol. I, p. 440, London, 1830.

[3] Thomas Southey, *Chronological History of the West Indies*, Vol. II, p. 407, London, 1827.

[4] Rev. J. Scherer, *op. cit.*, p. 178.

sity being greatest from Petit Goâve to Anse à Veau, but towns as far east as Port-au-Prince had houses thrown down or badly damaged. In the vicinity of Anse à Veau the sea withdrew and then broke with a crash on the shore.

Soundings indicate that the fault trough of southern Haiti continues westward as a topographic feature at least as far as the end of the Tiburon Peninsula; and, while it cannot be traced farther, the trend of the entire depression is in alignment with the southern scarp of the Bartlett Trough north of Jamaica. Evidence that the north coast of Jamaica is determined by a fault zone has been given elsewhere.[1] Briefly summarized, it is as follows:

1. The coast is an almost straight line from Port Maria to Montego Bay, a distance of nearly 113 km., where it is offset about 8 km. to the south and then continues westward to Pedro Point. The east-west line between Pedro Point and Montego Bay is continued eastward by the valley of Montego River which runs parallel to the coast for 16 km.

2. The land rises steeply from the sea to the plateau surface which has an elevation of 300 to 400 m. Wave erosion could not have produced these bluffs in the relatively short time that it has been active, and there is no broad, wave-cut terrace either above or below sea-level. The steep slopes continue below the sea and depths of 1,000 to 2,251 fathoms (1,829 to 4,117 m.) are attained within less than 15 km. of the shore.

3. There is a sudden change in slope both at the top and bottom of the escarpment.

4. The Tertiary beds terminate abruptly along the coast and in places the uplift has exposed the older underlying rocks.

5. The occurrence in modern times of several severe earthquakes with their epicenters a short distance off the coast indicates that there is here a zone of instability along which adjustments are still going on. The earthquake of 1692—one of the great catastrophes of history—and the destructive earthquake of 1907 both originated off the north coast of Jamaica and both were accompanied by sea-waves.

[1] Stephen Taber, "Jamaica Earthquakes and the Bartlett Trough," *Bull. Seis. Soc. Amer.*, Vol. X (1920), pp. 55–89.

Passing westward from Jamaica, soundings show that the steep southern escarpment of the Bartlett Trough continues toward Swan Island, and everywhere with abrupt changes in slope at top and bottom. Swan Island has the topographic characteristics of a horst which has remained standing within the zone of subsidence (see Fig. 1).

Great Swan Island is only 2.5 km. in length and about 20 m. in height; Little Swan Island is scarcely more than a reef. The submarine slopes in the vicinity of the islands are precipitous: on the south a sounding of 1,053 fathoms (1,926 m.) was obtained

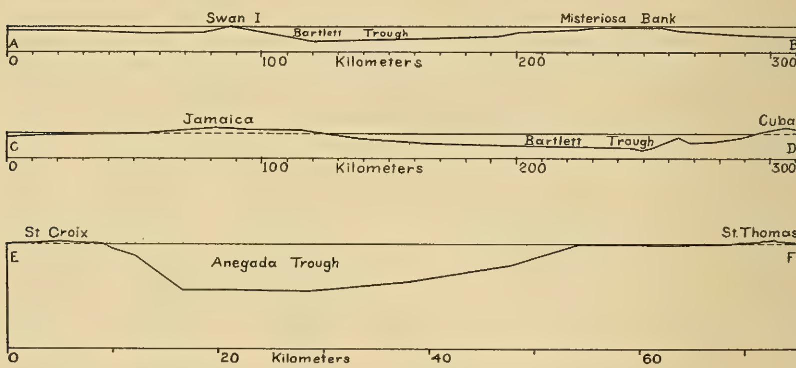


FIG. 1.—Profiles of the Bartlett and Anegada Troughs. Vertical and horizontal scales the same. Additional soundings would show the scarps to have steeper rather than gentler slopes.

within 10 km., the descent continuing until a depth of 2,136 m. is reached 16 km. from the island, after which the sea-bottom rises rapidly to the edge of the submerged Honduras-Jamaica Plateau; toward the north, a depth of 3,010 fathoms (5,505 m.) is attained within 32 km. of the island, thus giving an average slope of about one in six.

The latter sounding was obtained in a long, narrow depression lying at the foot of the scarp. The 3,000-fathom contour surrounding the depression (see map, Plate I) extends eastward from Swan Island along the base of the scarp for 200 km. or more. It has an average depth, below the floor of the Bartlett Trough in this vicinity, of over 1,000 m., the deepest sounding recorded being

3,206 fathoms (5,858 m.). The general form of this depression, in so far as it has been revealed by soundings, and its alignment with the fault trough of southern Haiti, together with the presence of other depressions of unknown shape nearer Jamaica, suggest that there has been more or less trough faulting all along the arc from Ocoa Bay to Swan Island.

Swan Island is built of limestone, mostly Pleistocene or Recent in age. A specimen from the higher part of the island consists chiefly of the coral, *Orbicella cavernosa* (Linn.). The particular form present in the specimen now lives in those waters and has not been found in deposits older than Pleistocene. In places the rock is a loosely cemented, coarse, calcareous sandstone. Pebbles and bowlders of hard limestone, containing terrigenous material, are abundant along the beaches. A specimen, showing well-defined, closely spaced bedding-planes and made up largely of *Globigerina* with amorphous silica filling the cavities, contained flakes of muscovite one millimeter in diameter and subangular quartz grains. Another specimen stained with ferric oxide, contained about 1.5 per cent Al_2O_3 as well as some quartz.[1] The land mass from which these terrigenous materials were derived must have been close at hand, but it has entirely disappeared.

It has not been possible to obtain seismologic data for Swan Island extending back over a long period of time, but during the summer of 1920 two shocks were felt.[2] On July 11 at 10:40 A.M. a distinct rumbling was heard, and this was immediately followed by a pronounced shock, apparently vertical, lasting five seconds. On August 18 at 6:04 P.M. a rather violent earthquake of approximately fifteen seconds' duration was experienced. The motion was reported as vertical and similar in character to that of the earthquake of July 11. No unusual sea conditions were noticed. Tools were dislodged in the engine-room and shop of the

[1] A set of rock specimens was procured from Swan Island through the courtesy of George S. Davis, General Manager of the Radio Telegraph Department of the United Fruit Company. The writer is also indebted to him for his kindness in furnishing seismologic data for Swan Island. The specimen of coral was identified by Dr. T. W. Vaughan, and the *Globigerina* by Dr. Jos. A. Cushman and Dr. Vaughan.

[2] These earthquakes were observed and reported by George H. Rogers, Chief Operator of the Swan Island Radio Station.

Radio Station, some falling from racks to the floor, but no damage resulted. The descriptions of these two earthquakes and the fact that they were not recorded on the seisomographs at Panama, Port-au-Prince, or Vieques indicate that they were local, probably originating close to Swan Island.

An earthquake at $11^h\ 01^m\ 46^s$ G.M.T. on January 1, 1910, was of sufficient intensity to throw two men out of bed. Instrumental records indicate an origin about 35 miles south of Swan Island but this determination is not regarded as very accurate.[1]

The submerged scarp bounding the Bartlett Trough on the south continues beyond Swan Island in a southwesterly direction and is especially well defined north of the Bay Islands (Utilla, Ruatan, and Bonacca) where it has a height of about 4,000 m. The Bay Islands are probably the eastern continuation of the Sierra de Omoa of Honduras[2] and they are also in alignment with Swan Island. Basalt-flows on the Island of Utilla and in the Sierra de Omoa at Chameleconcito near Puerto Cortez are believed by Powers to be Recent, perhaps Pleistocene in age;[3] and their presence is indicative of profound faulting such as has permitted the effusion of basalts in the fault trough of Southern Haiti.

Topographic evidence suggests that the separation of Jamaica and Haiti has resulted from faulting along a branch of the Swan Island–Jamaica–South Haiti fault zone, extending from a point near the north coast of Jamaica eastward along the south coast of Haiti until it joins the northern escarpment of the Caribbean Basin. The Tiburon Peninsula of Haiti continues westward beyond Cape Dame Marie as a submarine ridge for 150 km., passing through Navassa Island and Formigas Bank; a parallel ridge extends eastward from Morant Point, Jamaica, through Albatross Bank for a distance of over 100 km.; between the two lies a narrow channel having a nearly uniform depth of 2,000 m. Immediately south of the Tiburon Peninsula there are very steep slopes, especially near Vache Island and near Jacmel where soundings of over

[1] These data were supplied by Professor Harry Fielding Reid.

[2] Karl Sapper, "Über Gebirgsbau und Boden des südlichen Mittelamerika," *Petermann's Mitteil.*, Bd. 32, Heft 151 (1906), p. 17.

[3] Sidney Powers, "Notes on the Geology of Eastern Guatemala and Northwestern Honduras," *Jour. Geol.*, Vol. XXVI (1918), p. 514.

3,932 m. have been obtained within 20 km. of the coast. There is no evidence of important seismic activity along this branch zone east of Jamaica, and therefore, if the channel be due to faulting, as seems probably, a condition of at least temporary stability has been attained.

The Cayman Islands–Sierra Maestra–North Haiti Fault Zone.—This fault zone extends along the north side of the Bartlett Trough, crosses the Island of Haiti between Manzanillo Bay and Samana Bay, and, in the vicinity of Mona Passage, joins the fault zone which forms the south side of the Brownson Trough.

The Sierra Maestra range, after closely following the straight east-west coast of southern Cuba, continues westward as a submarine ridge, which, bearing slightly toward the south, reappears above the surface in the Cayman Islands and almost reaches the surface in the Misteriosa Bank. It culminates in the Pico del Turquino which rises abruptly from the sea to an altitude of 2,000 m. The precipitous southern slope of the range is continued below sea-level to depths of over 6,000 m., forming one of the most magnificent fault scarps known. At the base of this scarp, which forms the north side of the great Bartlett Trough, there is a narrow subordinate trough or series of elongated depressions containing four of the deepest soundings obtained in these waters; and it is interesting to note that these soundings are located opposite points where the top of the scarp is relatively high. The four soundings are: 5,501 m. immediately southeast of Misteriosa Bank; 6,269 m., 32 km. south of the Cayman Islands; 5,724 m., 35 km. south of Cape Cruz; and 6,412 m., 50 km. south of Turquina Peak. In passing south from Turquina Peak there is a precipitous descent to something more than 2,286 m. below sea-level, and then an ascent to 1,582 m. below sea-level before the descent to 6,412 m. is made (see profile, Fig. 1). Farther east there are other submerged peaks or ridges near the base of the scarp.

Vaughan has referred to the precipitous profiles along the south shore of Cuba as indicative of faulting and states that this interpretation is supported by the geologic structure.[1] The La Cruz marl

[1] T. W. Vaughan, "Some Littoral and Sublittoral Physiographic Features of the Virgin and Northern Leeward Islands and Their Bearing on the Coral Reef Problem," *Jour. Wash. Acad. Sci.*, Vol. VI (1916), p. 56.

(Miocene) is abruptly cut off by faulting at the shore line near the mouth of Santiago Harbor.[1]

Seismologic data are not available for the Cayman Islands, and because of sparse population little is known about the effects of earthquakes along the Sierra Maestra scarp except at Santiago de Cuba. This city, founded in 1514, has been repeatedly damaged by earthquakes.[2] Strong earthquakes were recorded at Santiago in 1578, 1675, and 1677. Kimball states that the city was destroyed by the shock of 1675,[3] but the writer has not been able to verify this statement. The earthquake of February 11, 1678, known in Cuban tradition as the *great earthquake*, caused enormous destruction in Santiago; and exactly one year later the cathedral was destroyed by another shock. The severe earthquake of 1755 was accompanied by a sea-wave which almost completely inundated the town. The strongest earthquake recorded at Santiago, according to Salterain, occurred June 11, 1766, and it was followed by a large number of aftershocks. Many buildings were completely destroyed and others were badly damaged. Between 1777 and 1852 eighteen important earthquakes are listed by Salterain, the earthquake of August 20, 1852, and its aftershocks being especially severe.

In contrast with the Sierra Maestra region the north and central parts of Cuba have been virtually free from seismic disturbances. A severe earthquake followed by aftershocks originated in the Sierra de los Organos of western Cuba in 1880, but, before that time and since, earthquakes have been almost unknown in that section.

Passing eastward from the Bartlett Trough the fault zone is marked by a depression which obliquely crosses the Windward Passage and extends between Tortuga Island and the coast of Haiti. The depression enters Haiti through Manzanillo Bay, and,

[1] T. W. Vaughan, "Geological History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 626.

[2] Most of the facts concerning Cuban earthquakes given in this paper have been abstracted from "Ligera Reseña de los Temblores de Tierra Occuridos en la Isla de Cuba" by P. Salterain, *Boletin de la Comisión del Mapa Geôlogico de España*, Vol. X, pp. 371–85, Madrid, 1883.

[3] R. B. Kimball, *Cuba and the Cubans*, p. 20, New York, 1850.

as a land valley, crosses the island to Samana Bay, a distance of 240 km. This great valley was named the Véga Real by Columbus in 1494, but now the name is usually limited to the eastern portion. It is very similar topographically to the great valley of southern Haiti. The floor of the valley, less than 25 km. in width, consists of a series of broad plains lying between the Sierra de Monte Christi on the north and the Grande Hilera on the south. The valley is drained by two rivers, the Yaqui del Norte and the Yuma, flowing in opposite directions.

The geologic structure of the valley has not been studied in detail. Cooke,[1] who has recently visited the region, states that the south front of the Cordillera Sententrional (Sierra de Monte Christi) is a fault scarp which brings up Eocene and Cretaceous rocks high above upper Miocene. The displacement is therefore in the same direction as along the Sierra Maestra fault. Cooke found several faults of slight displacement along the Gurabo River near the southern side of the Véga Real and states that these are probably normal, with uplift on the north. There are other faults of much greater magnitude near the southern side of the Véga Real and in the adjacent part of the Cordillera Central, but no data are now available concerning them. Cooke believes that faulting has been an important factor in shaping some of the boundaries of the Véga Real, but he does not regard the valley as a simple down-dropped fault block.

The high seismicity of the great northern valley of Haiti was recognized by Scherer, who states that the first great earthquake mentioned in histories of Haiti occurred here in 1564. It resulted in the destruction of Conception de la Véga and Santiago de los Caballeros, two cities in the Véga Real about 30 km. apart. In 1783 the principal church at Santiago was partly thrown down by an earthquake and several buildings were destroyed.

The earthquake of May 7, 1842, was one of the most severe recorded on the island. Destruction was greatest at Cap Haitien, a city of ten thousand inhabitants, which lost half of its population. The intensity was almost equally as high at Môle St. Nicolas,

[1] Dr. C. W. Cooke kindly furnished information concerning the geologic structure of the Véga Real in letters dated January 26, and October 5, 1920.

Port de Paix, Fort Liberté and Santiago de los Caballeros, all of which were destroyed with the loss of several thousands of lives. At Cap Haitien waves dashed against buildings along the quay; at Port de Paix the sea withdrew 60 m. and, upon returning, buried the city under 4 or 5 m. of water. The bed of the Yaqui River is said to have been suddenly elevated, driving its waters both up and down stream. The shock was severe at Santiago de Cuba and was felt throughout the length of the Sierra Maestra. The distribution of intensities and the phenomena of the sea-wave indicate that the earthquake was caused by a vertical displacement along a fault passing between Tortuga Island and St. Nicholas Peninsula.

The earthquake of December 29, 1897, seems to have originated in the central part of the Yaqui Valley, the intensity being greatest between Guyaubin and Santiago and at Altamira. At Guyaubin and Santiago great cracks were formed and subsidence of the ground was reported.

Scherer correlates the disastrous earthquake of September 23, 1887, with the great northern valley, but the writer thinks that it was caused by a vertical displacement along a fault near the east end of the Bartlett Trough, a short distance south or southwest of Môle St. Nicolas. The destruction was greatest at Môle St. Nicolas, nearly all of the houses being thrown down. Buildings were also damaged or destroyed at Cap Haitien, Port de Paix, Gonaïves, and other places. A sea-wave followed the earthquake and was reported from points along the shores of Gonaïve Gulf as far as Anse d'Hainault on the end of the Tiburon Peninsula; at Jérémie on the north coast of the Tiburon Peninsula the sea withdrew 20 m. and returned with a rush. Along the north coast of the St. Nicholas Peninsula, however, the wave seems to have been of no importance. The shape of the St. Nicholas Peninsula suggests that both its north and its south coasts may have been determined by faulting.

Three other Haitian earthquakes of moderately high intensity cannot be correlated with either of the great fault valleys. One originated in the eastern part of the island in 1882 and damaged the churches at Seybo and Higuey; another, which occurred October 6, 1911, was of highest intensity in the central part of the

island and probably originated on the south flank of the Grande Hilera or in the central valley of Haiti. This valley, according to Jones, was formed by folding and erosion rather than by faulting.[1] The earthquake of April 23, 1916, which damaged buildings at Boya, Guerra, and Bayaguana, seems to have originated near latitude 18° 45′ N., longitude 69° 45′ W.

The separation of Cuba and Haiti has been attributed by Vaughan to the downthrow of a block between two faults; one forming the north side of the Bartlett Deep, the other forming the south side and converging toward the former in the Windward Passage.[2] The evidence summarized in the present paper indicates that the separation of the two islands is to be correlated with the formation of the series of depressions, including the Véga Real, which mark the Cayman Islands–Sierra Maestra–North Haiti fault zone, and which have probably originated through differential displacement of relatively narrow blocks or wedges within that zone.

A narrow trough, 3,058 to 4,353 m. in depth, separates the Island of Haiti from the Bahama Banks. It extends eastward, in a great arc convex toward the north, from a point north of the Windward Passage and enters the Brownson Trough northeast of the Samana Peninsula. The topographic characteristics of this trough and its parallelism to the two Bartlett Trough fault zones suggest that it has originated through faulting; but no geologic evidence of faulting is known and little seismologic evidence is available except for the extreme eastern end where it joins the Brownson Deep (see page 106).

THE BROWNSON TROUGH

The Brownson Trough, containing the deepest sounding made in the Atlantic Ocean, parallels the Porto Rico–Virgin Islands ridge on the north. Its shape is not known in detail for as yet few soundings have been made in these waters. The 4,000–fathom contour surrounds a narrow area, about 320 km. long in an east-west direction; and the 3,000-fathom contour which is approxi-

[1] W. F. Jones, *op. cit.*, *Jour. Geol.*, Vol. XXVI (1918), pp. 735–36 and Plate V.

[2] T. W. Vaughan, "Geologic History of Central America and the West Indies During Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), pp. 625–26.

mately concentric extends nearly three times as far. The trough is deepest near its western end.

On the south the trough is bounded by a great scarp that rises steeply to the plateau-like ridge on which Porto Rico and the Virgin Islands stand, the average slope being about one in thirteen. The rectilinear north coast of Porto Rico and the steep submarine scarp descending from it are indicative of faulting. This coast is bordered, near the west end of the island, by a long line of high cliffs which evidently represent a fault scarp, for the youthful topography of the plateau back of the cliffs and the gorge-like valley of Guajataca River near its mouth testify to a recent elevation of the land, whereas a long period of time would be required for the sea to cut such cliffs in gently dipping rock strata. A wave-cut bench at the foot of the cliffs marks the latest uplift of the land, amounting to several meters; and a similar sea-terrace bordering Desecheo Island proves that this recent elevation extended at least that far westward.[1] The abrupt change in the slope near the 100-fathom contour about 8 km. north of the sea-cliffs and the occurrence of earthquakes at points lower down along the slope indicate the presence of a zone of faulting, and suggest that the descent into the trough is not accomplished by a single fault scarp.

The fault zone along the south side of the Brownson Trough is possibly the eastward extension of the Cayman Islands–Sierra Maestra–North Haiti fault zone, but if so, there is a sharp flexure in the trend of the zone immediately north of Mona Passage, and the downthrow changes to the opposite side. The topography of this critical region, in so far as it has been revealed by soundings, suggests that the ends of the two zones overlap and intersect; and this may explain the origin of the peculiar submarine valley, which, heading in Aguadilla Bay, extends northwestward into the Brownson Trough. This valley was described and figured in a previous paper.[2] At Aguadilla the coast has been slowly sinking during the last half-century, while at Mayagüez, 23 km. farther south as well

[1] Harry Fielding Reid and Stephen Taber, "The Porto Rico Earthquakes of October–November, 1918," *Bull. Seis. Soc. Amer.*, Vol. IX (1919), p. 120.

[2] *Ibid.*, pp. 118–21 and Plates 13 and 14.

as along the north coast the land has been rising. The seismicity of the region immediately north of Mona Passage is high.

Many earthquakes have been recorded in Porto Rico and the Virgin Islands.[1] Most of them have had a low intensity and have been reported from only one or two places, so that it is impossible to determine accurately their epicenters, but it is usually possible to locate, approximately at least, the epicenters of the stronger shocks. If consideration is limited to earthquakes which have had a probable maximum epicentral intensity of above VI in the Rossi-Forel scale, it is found that, with very few exceptions, they have originated along the steep slopes descending into the Brownson or the Anegada troughs.

The earthquake of April 16, 1844, which damaged buildings at Isabela on the north coast of Porto Rico, probably had its origin a short distance north or possibly northwest of the island. The shock of November 28, 1846, was most strongly felt in the northwestern part of Porto Rico where some buildings were injured, the distribution of the intensity indicating an origin off the northwest coast. The earthquake of October 11, 1915, which was felt over most of Porto Rico and as far west as Puerto Plata, Santo Domingo, probably originated a short distance north of Mona Passage.

The destructive earthquake of October 11, 1918, with its accompanying sea-wave, and the strong aftershocks of October 18 and 24 and November 12, as well as a host of weaker shocks felt during 1918–19, all originated a few kilometers west of Point Borinquen on the northwest coast of Porto Rico.

Other earthquakes have originated at points farther east along the southern scarp of the Brownson Trough. On the night of December 8, 1875, an earthquake, which probably had its epicenter a short distance north of the coast, damaged buildings in Arecibo. The earthquake of September 27, 1906, having an epicentral

[1] A catalogue of earthquakes felt in Porto Rico and the Virgin Islands from 1772 to 1918 was given in "The Porto Rico Earthquake of 1918 with Descriptions of Earlier Earthquakes. Report of the Earthquake Investigation Commission," by Harry Fielding Reid and Stephen Taber, *Document No. 269*, U.S. House of Representatives, 66th Congress, 1st Sess. (1919), pp. 53–66.

intensity close to IX R.-F., originated about 50 km. north of the coast and opposite the middle of the island; and the shock on September 5, 1908, with slightly lower intensity seems to have had its origin in approximately the same locality. On July 7, 1869, two light shocks were felt on board the ship *Esther and Sophie* when about 20 km. north of Culebra Island. The earthquake of February 17, 1909, felt over the greater part of Porto Rico and the Virgin Islands, originated along the steep submarine slopes north of Culebra and St. Thomas. On October 29, 1886, an earthquake was felt on board the British brigantine *Wilhelmina* while over the steep scarp 75 km. north of Anegada Island.

The north side of the Brownson Trough is entirely under water few soundings have been made in its vicinity, and it is so far from the land that earthquakes originating along its slopes could cause little or no damage; therefore evidence of faulting is not abundant. A broad ridge rising 3,200 to 5,600 m. above the floor of the trough separates it from the North Atlantic Basin. The trough-like depression separating Haiti from the Bahama Banks apparently joins the north slope of the Brownson Trough at a slight angle, in much the same way that the Cayman Islands–Sierra Maestra–North Haiti fault zone joins the fault zone on the south side of the Brownson Trough.

On February 19, 1883, the bark *Siddartha* experienced a sharp earthquake, lasting 25 seconds, while over the north side of the Brownson Trough in lat. 20° 04′ N., long. 67° 41′ W. The bark trembled as if dragging over a hard bottom although the depth here is more than 6,000 m.

On November 29, 1916, and on July 13 and 26, 1917, severe earthquakes originated in the vicinity of lat. 19° 30′ N., long. 68° 30′ W. The last of these shocks was felt over most of Haiti and Porto Rico and probably had an intensity of IX R.-F. near the epicenter. It was followed by a series of aftershocks lasting several days. These earthquakes of 1916 and 1917 should be correlated, perhaps, with the trough that separates Haiti from the Bahama Banks for they originated in the area where it joins the Brownson Trough (see page 103).

THE ANEGADA TROUGH

The Anegada Trough, separating Porto Rico and the Virgin Islands group from St. Croix and the Lesser Antilles is the deepest of the many passages connecting the Caribbean Sea with the Atlantic Ocean. A description of this trough accompanied by a map and transverse profile was given in a previous paper.[1]

It is deepest midway between St. Croix and Vieques where a sounding of 2,501 fathoms (4,574 m.) was obtained; here it extends nearly east and west for 100 km. Between St. Croix and the islands of St. Thomas and St. John the depth is over 2,000 fathoms. Farther east the trough rises until the depth is a little over 1,000 fathoms and there it bifurcates. One branch seems to extend northeast and join the Brownson Trough about 60 km. northeast of Anegada Island, where the depth is over 3,000 fathoms; the other extends eastward in the direction of St. Martin but is not well defined. In its deeper parts the trough is about 40 km. in width between the tops of the inclosing scarps, which show abrupt changes in slope at both top and bottom. The floor of the trough is relatively flat.

The south side of the trough near St. Croix and westward therefrom is bounded by a tremendous fault scarp (see profile Fig. 1). Near Harms Bluff at the northwest corner of St. Croix the scarp descends 4,348 m. in 8 km., an average slope of 30°. For a distance of 4.4 km. the slope averages over 37°, and for shorter distances it is much steeper. Vaughan states that the faulting has taken place so recently that the sea has barely cut a niche into the fault plain.[2] The northern scarp of the trough does not touch the coast of any of the islands; it lies 15 km. south of St. Thomas and 6 or 7 km. from Vieques. It is not so precipitous as the opposing scarp, the average slope being about 12°, though in places it is much steeper.

[1] Harry Fielding Reid, and Stephen Taber, "The Virgin Islands Earthquake of 1867–1868," *Bull. Seis. Soc. Amer.*, Vol. X (1920), pp. 20–25.

[2] T. W. Vaughan, "Some Features of the Virgin Islands of the United States," *Asso. Amer. Geog. Ann.*, Vol. IX (1920), pp. 78–82.

Several severe earthquakes have originated in the Anegada Trough and many light shocks are recorded by the seismographs on the Island of Vieques. A severe earthquake was felt in Antigua, St. Christopher, and Tortola July 11, 1785. Since the shock was strongly felt on all three islands its epicenter was probably between them; and the report that cracks were formed in the ground in Tortola suggests an origin in the vicinity of that island.

A severe shock was felt in St. Thomas, April 20, 1824. The precise location of the epicenter cannot be determined from the data available but is not far from St. Thomas, probably in the Anegada Trough, though possibly on the opposite side of the island along the southern scarp of the Brownson Trough. The strong shock reported from St. Thomas September 19, 1853, and the two felt on May 12, 1865, appear also to have originated near that island.

The great earthquakes of November 18, 1867, originated along the northern scarp of the trough 15 to 20 km. south of St. Thomas. There were two strong shocks separated by an interval of about 10 minutes, both being followed by sea-waves. Aftershocks continued for several months, the strongest occurring December 1 and 12, 1867; January 5 and March 17, 1868, and September 17, 1869. The shock on March 17, 1868, was accompanied by a small sea-wave and seems to have had its epicenter a little farther west than the others, though all originated along the same scarp.

On July 24, 1913, a severe earthquake was felt in the Virgin Islands and throughout Porto Rico except along the west coast. The epicenter was apparently in the Anegada Trough near latitude 18° 30′ N., longitude 64° W.

THE NORTHERN ESCARPMENT OF THE CARIBBEAN BASIN

The Caribbean Basin is bounded on the north by an escarpment that descends steeply from Porto Rico and Haiti to a depth of 4,572 m. within 90 km. of the islands. This is the only important scarp in the region that does not form one side of a relatively narrow trench. It gives the Porto Rico–Virgin Islands ridge, extending eastward from Haiti, the topographic characteristics of a great horst.

Near Ponce on the south coast of Porto Rico, Berkey has traced an east-west fault which he thinks is of very late Tertiary age.[1] It brings the older rocks of the pre-Tertiary into contact with the younger series forming the present coastal margin. This fault may be one of a series by which the descent to the floor of the Caribbean Basin is accomplished. There is, however, no topographic evidence of recent displacements along it; and the Seismic history of the region indicates that, if the Caribbean scarp be due to faulting, it is now relatively stable. The epicenter of no earthquake can be definitely assigned to this scarp, although some of the shocks reported only from the south coasts of Porto Rico and Haiti may have originated there. Certainly no disastrous earthquakes and comparatively few light shocks have occurred there in several centuries.

On August 4 and 13, 1908, moderately strong shocks were felt at Ponce and neighboring points. The intensity was about VI R.-F., and some buildings were slightly damaged. The origin was probably not far from Ponce.

Earthquakes of low intensity have originated at many places in Porto Rico, but in contrast with the north coast none has had an intensity of more than VI or VII. A shock on August 30, 1865, which slightly damaged churches at Manatí and Ponce, probably had its origin near the center of the island. On October 23, 1860, an earthquake with intensity of VI–VII caused some damage at Mayagüez on the west coast, and the epicenter was probably not far away. Several light shocks have originated in the eastern part of Porto Rico near Cidra, the strongest, on October 22, 1901, having an intensity of about VI.

RELATION OF FAULT ZONES TO EARLIER TECTONIC TRENDS

The fault zones described in this paper collectively form a great fault system which extends from the eastern end of the Brownson Trough westward to the Gulf of Honduras, a distance of 2,500 km. The two fault zones inclosing the Bartlett Trough are apparently in alignment with the Matogua Valley and the

[1] C. P. Berkey, "Geological Reconnoissance of Porto Rico," *Ann. N.Y. Acad. Sci.*, Vol. XXVI (1915), p. 40.

Polochie–Lake Izabal Valley in Guatemala, but Powers who has recently visited the region states that he believes these valleys are due to erosion dependent on folding.[1] Sapper,[2] in mapping the tectonic lines of Central America attributes the east-west ranges of Guatemala to folding, and this view has been adopted by other geologists. If the Antillean fault zones continue westward beyond the Gulf of Honduras their curvature is reversed, for in Central America the mountain ranges extend in approximately parallel arcs convex toward the south.

The Central American ranges, as they approach the Gulf of Honduras, curve gradually toward the northeast, and therefore meet at an angle the north coast of Honduras which extends east and west. Powers states that this coast is evidently a fault-zone area.[3] Vaughan correlates the tectonic lines of Honduras with the submarine ridge or plateau connecting the Honduras Peninsula with Jamaica,[4] but this feature is abruptly terminated by the fault scarp north of Jamaica. The tectonic lines of Central America, according to Sapper, are of several different ages; some having been formed in the Paleozoic, others as late as the Tertiary. Possibly some of these lines continue into the West Indies with curvature convex toward the south while others turn gradually southward and become convex toward the north. Faulting in Central America may have followed along the old structural lines due to folding. The location of Guatemala in a belt of high seismicity that may be traced from the Greater Antilles through Central America and Mexico into California, together with the precipitous topography of the region suggest that the great Antillean fault system may extend into Central America, and, gradually curving toward the north, continue into California. These questions cannot be decided, however, until more field data are available.

The Sierra de los Organos, which form the backbone of western Cuba, have a northwest-southeast trend and may be genetically

[1] Sidney Powers, written communication dated September 10, 1920.

[2] Karl-Sapper, *op. cit.*

[3] Sidney Powers, written communication dated September 10, 1920.

[4] T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 618.

related to the tectonic lines of Central America and southeastern Mexico.

Another group of tectonic lines, prominent in the Greater Antilles, trends northwest and southeast. The principal mountains of Jamaica, composed of intensely folded Cretaceous rocks trend about N. 70° W. parallel to the northeast coast; the Grand Hilera or Sierra Cibao extend across the Island of Haiti in a northwest-southeast direction from a point near Cape Engano to Môle St. Nicolas, and the axis of elongation of Cuba from the Windward Passage almost to Habana also follows this trend. Vaughan infers that a fault runs northeast from Cape Cruz but the evidence is meager.[1]

Another old structural direction, which seems to have no relation to the present topography, is indicated by the north-south strike of the crystalline rocks exposed on the Isla de Pinos lying south of western Cuba.[2]

The Antillean fault zones cut across the earlier trend lines which seem to be due chiefly to folding, and, because of their recency as well as the magnitude of the displacements, they dominate the present topography. Transverse faulting seems to be rare, and it has had little or no effect on the topography. The irregular coast lines at the east and west ends of the various islands are in marked contrast to the rectilinearity of many of the coast lines that run east and west.

Berkey has suggested that Porto Rico is a large fault block uplifted along the southern margin and tilted toward the north with breaks at each end. In support of this hypothesis he mentions the unsymmetrical position of the main drainage divide, which is nearer the south coast; the comparatively abrupt termination of the island at both ends; and the absence of the younger limestone margin from these coasts although it is fairly continuous along the north coast and about half of the south coast.[3]

[1] T. W. Vaughan, "Fossil Corals from Central America, Cuba, and Porto Rico, with an Account of the American Tertiary, Pleistocene, and Recent Coral Reefs," *U.S. Nat. Mus. Bull. 103* (1919), pp. 288–89.

[2] C. W. Hayes, T. W. Vaughan, and A. C. Spencer, "Report on a Geological Reconnaissance of Cuba," Washington, 1901.

[3] C. P. Berkey, *op. cit.*, pp. 40–41.

In opposition to this view it may be urged that the east and west ends of Porto Rico are rather irregular; that there is neither topographic nor seismologic evidence of faulting; and that the absence of Tertiary limestones from the ends of the island may be due to submergence. The numerous reefs, projecting rocks, and small islands extending eastward from Porto Rico as far as Anegada are proof of subsidence at this end of the island; and at the other end the water is relatively shallow between Porto Rico and Haiti, averaging less than 450 m., while Mona and Desecheo islands rise above the surface. Semmes attributes the present position of the drainage divide to greater rainfall on the north side of the island.[1]

ORIGIN OF THE ANTILLEAN TROUGHS

The great troughs of the Antilles are bounded by fault zones, and are characterized by great depth, by precipitous inclosing scarps which show abrupt changes in slope at top and bottom, and by relatively flat floors that, instead of being graded like river valleys, rise and fall throughout their length. Many of the deepest places are close to the inclosing scarps instead of near the centers of the troughs, and occasional horst-like elevations are also found within the fault zones. The troughs are parallel rather than convergent and in places are roughly arranged *en echelon.*

All of the evidence is in accord with the conclusion that the troughs have been formed through faulting. Moreover, they must be attributed to subsidence of long narrow blocks rather than elevation of the areas on each side; for the rock strata exposed in the marginal scarps standing above sea-level were laid down in relatively shallow water, and portions of the larger islands have remained continuously above sea-level since pre-Tertiary time, while the faulting is more recent. The subordinate depressions at the base of the main scarps are also indicative of normal faulting, and there is an absence of lateral pressure effects such as would be expected to accompany thrust faulting.

Vaughan is of the opinion that the faulting took place in late Tertiary, probably Pliocene time, and he cites three kinds of evi-

[1] D. R. Semmes, "The Geology of the San Juan District, Porto Rico," *Scientific Survey of Porto Rico and the Virgin Islands, N.Y. Acad. Sci.*, Vol. I, Part I (1919), p. 38.

dence, namely: (1) The faulting along the south coast of Cuba is subsequent to old or middle Miocene, as the Miocene La Cruz marl is abruptly cut off at the shore; (2) the sea has had time to cut only narrow benches into the fault scarps that form shore lines; and (3) the biological evidence demands land connection in late Tertiary time between Cuba, Santo Domingo, Porto Rico, and thence to South America.[1]

The faulting may date from the Pliocene, as suggested by Vaughan but the frequent occurrence of earthquakes along the fault zones proves that the displacements are still continuing; and the sea-waves, which have accompanied nearly all of the great earthquakes with the exception of those originating in the Haitian land valleys, indicate that these latest displacements have also been vertical. Another evidence of recent displacements is furnished by the character of the material on the sea-floor along the fault zones. Off the northwest coast of Porto Rico broken coral is found at a depth of 1,864 m. and the bottom is "rocky" at 3,221 m.[2]

The Antillean fault system, whether it continues into Central America or not, forms one of the major structural features of the earth; and the displacements now going on are similar to those which have occurred in the past. The earthquakes are not limited to the immediate vicinity of land areas and hence cannot be attributed to adjustments resulting from changes in surface-loading due to erosion. That the faulting extends to profound depths is shown by the persistence of the fault zones, by the great height of the scarps, and by the extrusion of lava from some of the fault fractures.

The total volume of lava that has reached the surface along the Antillean fault zones is insignificent as compared with the size of the troughs; consequently there can be in this instance no causal relation between volcanic activity and the foundering of the narrow blocks, such as has been suggested for the Christiania Fiord in southern Norway, the "rift valley" of eastern Africa and similar troughs elsewhere.

[1] T. W. Vaughan, "Geologic History of Central America and the West Indies during Cenozoic Time," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 626.

[2] United States Coast and Geodetic Survey Chart 901.

Fault phenomena of the type exhibited in the Antilles testify to a state of tension rather than compression in the earth's crust. This tension is difficult to explain. It may be due to warping, for there is some evidence that the formation of the troughs has been accompanied and perhaps, in part, preceded by an upswelling or arching of the region together with more or less subsidence of the border portions. The uplift has culminated in the Island of Haiti, and the Bartlett Trough has developed along the axis of uplift, the surface being in most places higher near the borders of the trench than farther back. Sea-terraces, marking intermittent elevations have been observed along many coasts of the Antilles; in Cuba they extend entirely around the east end of the island but attain their finest development along the south coast between Cape Maisi and Guatanamo.[1] On the opposite side of the trough near Montego Bay, Jamaica, they are also well developed, Hill having observed six distinct benches.[2]

While the evidence is extremely meager it is at least in accord with what is known concerning the structural relations of fault troughs in the other parts of the earth. Most of these troughs appear to have been formed as a result of the upswelling of broad arches and plateaus of the downwarping of basin-like areas under the influence of forces that probably have acted vertically.

[1] R. T. Hill, *Cuba and Porto Rico with the Other Islands of the West Indids*, p. 44, New York, 1899.

[2] R. T. Hill, "The Geology and Physiography of Jamaica: Study of a Type of Antillean Development," *Bull. Mus. Comp. Zoöl. Harvard College*, XXXIV, Geol. Ser. 4 (1899), p. 31.

THE CHARACTER OF THE STRATIFICATION OF THE SEDIMENTS IN THE RECENT DELTA OF FRASER RIVER, BRITISH COLUMBIA, CANADA[1]

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OUTLINE

INTRODUCTION

During the course of an investigation, carried on during parts of 1919 and 1920 by the Geological Survey of Canada in co-operation with the Department of Public Works, of the characteristics of Fraser River, British Columbia, an opportunity was afforded of studying the character and mode of origin of the stratification of the sediments forming the Recent delta of the Fraser. Bottom samples were obtained by means of a bottom-sampling machine which furnished core samples (1) from the sea-bottom deposits in the Strait of Georgia, and (2) from the fresh-water deposits in Pitt Lake, a tidal lake tributary to the Fraser. The object of this paper is to describe the character and mode of origin of the stratification of the Recent delta deposits of the Fraser River, and to contrast the character of the stratification of the sediments being formed in fresh water with that of the sediments being formed in salt water.

The writer is indebted to Dr. W. Bell Dawson, superintendent of the Tidal and Current Survey, Department of the Naval Service, Canada, for information regarding the tides and tidal currents in Fraser River and in Pitt Lake, and to Mr. C. C. Worsfold, district engineer, Department of Public Works, Canada, for information regarding the tides and freshets in Fraser River.

[1] Published by permission of the Director of the Geological Survey, Canada.

FRASER RIVER AND ITS RECENT DELTA

The Fraser River is the largest river in British Columbia whose basin lies entirely within the province. It has a length of 790 miles and drains an area of 91,700 square miles. The maximum discharge of the river at Hope (100 miles above its mouth) for the past nine years, as determined by the Dominion Water Power Branch of the Department of the Interior, was in July, 1920, when it amounted to 380,000 c.f.s. During the great flood of 1894, however, the discharge as estimated by officials of the Department of Public Works was nearly 500,000 c.f.s. The average minimum discharge of the river at Hope for the past nine years was 17,000 c.f.s., the lowest being 12,000 c.f.s. There is thus considerable variation from high to low water in each year. The water usually begins to rise in May and reaches its greatest height in June or July. Extreme low water may occur in any month from November to March. During the low-water period the river is affected by ocean tides for a distance of 60 miles above its mouth. The current is reversed in the river by the flood tide, however, only for 30 miles above the mouth. The tides in the Strait of Georgia are declinational in character and are characterized by marked diurnal inequality of the semidaily tides. The mean range at the mouth of the Fraser River is 6.4 feet. The maximum range of the great flood tides is 15 feet and of the great ebb tides 14 feet. These maximum ranges, however, are rarely reached, the average for the large tides—which occur for a few days twice a month near the time of maximum declination of the moon—being about 12 feet for the ebb tides and 13 feet for the flood tides. During the balance of the month the ranges are less. The fact that the river is tidal for a considerable distance above its mouth renders it navigable; for the lack of river water during the low-water stage of the river is largely compensated by the tidal water. The combined ebb-tidal and river discharge of the river, in the main channel near its mouth, is rarely less than 100,000 c.f.s., even during the extreme low-water stage of the river.

The water of the Fraser River is turbid to some extent throughout the year, and is markedly so during freshets; but the amount of material carried in suspension is comparatively small. The

average amount of material carried in suspension, as shown by analysis of composite samples of the river water collected triweekly at New Westminster for the period of one year from June 5, 1919, to June 5, 1920, was 62 parts per 1,000,000, and the maximum 230 parts per 1,000,000. The high turbidity of the water is due to comparatively large amounts of very fine material carried in suspension. About half the material carried in suspension during the freshet is composed of silt and clay, a part of which is so fine that it can with difficulty be removed by filtering. The river in its seaward part carries in suspension little material coarser than very fine sand (0.1 to 0.05 mm.), but considerable quantities of medium and coarse sand are moved along the bottom. During the freshet the turbid river water flows out over the sea water in the Strait of Georgia and extends for distances of 10 to 15 miles from the mouth of the river. The color line marking the contact of the river water and the sea water is a striking feature in the Strait of Georgia, near the mouth of the river, where it oscillates backward and forward according to the varying influences of the river, tidal, and wind-induced currents.

The velocities of the currents in the lower part of the river near its mouth vary greatly with the tides and according to the stage of river water. During the freshet the maximum velocity of the combined river and ebb-tidal currents reaches, but rarely exceeds, $5\frac{1}{2}$ knots per hour. During the low-water stage the maximum velocity is about $3\frac{1}{2}$ knots. The inward-flowing flood-tidal current rarely, even during the lowest stage of river water, equals the outward current, although the rise of tide on the flood is more rapid than the fall on the ebb. The ebb-tidal current is the dominant current because it is reinforced by the river current. The sea water enters the river during the freshet only to a very small extent, and only along the bottom of the main channel. During the low-water stage the sea water at times extends on the flood tide as much as 8 miles up the river. The flood-tidal current in the Strait of Georgia runs north and is the dominant tidal current. It has a maximum velocity of about 2 knots. Slack water is very pronounced in the lower part of Fraser River, because of the lack of a deep channel where it enters the river, which

prevents sea water from entering the river in flood tide until the tide has reached a considerable height.

The Recent or modern delta of Fraser River has its head, as defined by the point where the first distributary is given off, at the city of New Westminster. It extends west for 19 miles to the Strait of Georgia and, across its seaward front, is 14 miles wide. The surface of the delta is all below the level of high tide, except in a few places, where the surface of peat bogs is a few feet above the general level and the delta land high enough to be reclaimed; this is diked to exclude the flood-tidal and freshet waters. At New Westminster the river is confined between drift ridges or upland areas, which rise 200 to 300 feet above the river. The upland area south of the river marks the inner edge of the delta and extends from a point on the river 3½ miles below New Westminster nearly straight south to Boundary Bay. The delta is bounded on the north by the highland area extending from New Westminster nearly west to Point Grey. In its seaward part on the south side it is interrupted by the highland area of Point Roberts, an island-like drift hill, which has been joined on to the mainland by the construction of the delta. The North Arm of the Fraser flows along the northern border of the delta, the main Fraser flows through the central part, and in the southern part there are a number of smaller outlet channels.

There can be no doubt that the materials composing the delta have been transported to their present resting-place very largely by the river; for it has been shown that the river transports considerable material during its freshet stage, and there is no other apparent source for such a large amount of material. A small part, however, has been and is being derived from wave erosion of the shores, chiefly of the highland area of Point Roberts. A large part of the material composing the delta is sand and silt derived by stream erosion from the vast accumulations of glacial drift which border the banks of the Fraser and Thompson rivers for long distances above the canyon of the Fraser, in smaller part from erosion of the bedrock (granite) in the canyon of the river, and from erosion of the drift deposits in the upper part of the delta area.

The delta is building out into fairly deep water in the Strait of Georgia in spite of the facts that the river is tidal for a considerable distance above its mouth, with a mean tidal range of 6.4 feet and a maximum range of 15 feet at its mouth, and that the seaward front of the delta is swept by fairly strong tidal currents. The out-building occurs because of the dominance of the river currents over the tidal currents. The river currents are strong enough to transport large quantities of coarse and fine material which the tidal currents cannot transport into deep water. The tides and tidal currents have the effect, however, of giving an unusual form to the seaward portion of the delta. In its seaward portion the river flows for several miles through sand banks exposed in large part at low tide, but completely submerged at high tide. These banks extend seaward on an average of 4 to 5 miles from the higher delta land and are for the most part nearly level except where channeled by outlet streams. The flood tides and tidal currents tend to cause a diffusion and diversion of the river currents in this part of the delta and prevent the river from building up its banks. The coarse material in the sand banks is gradually moved seaward by the dominance of the combined ebb-tidal and river currents, which tend to carry it seaward, over the flood-tidal currents moving inward. The fine material is kept in suspension until it is carried seaward by the river currents and settles by gravity and through the influence of sea water in causing it to flocculate, or is carried inshore by the flood-tidal or wind-induced currents and lodges in the grass-covered marshes and slack-water channels, tending to build them up and extend the higher delta land seaward. The flood-tidal currents also have the effect of giving to the greater part of the subaqueous front of the delta a smooth, curved outline lacking the finger-like projections characteristic of many deltas.

In structure, the delta presents the forms characteristic of a high-grade delta built into fairly deep water. The fore-set beds are well developed and extend from the 3-fathom line to about the 30-fathom line and have an average dip of about 10°. The dip, however, is irregular, and in places the subaqueous front of the delta is nearly vertical for heights of 1 to 3 fathoms. Below the

30-fathom line the beds slope more gradually seaward, the 100-fathom line being reached at from 1 to 2 miles from the outer edge of the sand banks. The horizontal bottom-set beds, consisting of very fine material, occupy the bottom over a considerable part of the Strait of Georgia, off the mouth of the river. The strait, which is 10 to 15 miles wide, varies in depth in its central part from 100 fathoms to about 225 fathoms. The top-set beds are thinnest and in most places only a few feet in thickness. In places, however, they may be upward of 100 feet thick, as, for example, where a deep channel of the river has been abandoned and has been gradually filled and built up to high-tide level. The top-set beds are sandy in character in their lower part up to about half-tide level, the upper part being silty in character. The silty, fine-grained beds, formed by deposition from flood waters overflowing the river banks, become thicker, progressively, upstream, owing to the fact that freshet waters do not affect the level of high tide in the lower part of the river as far up as Steveston, 6 miles above the mouth, but appreciably affect the level in the upper part of the river. The shore face of the delta is very weakly developed because wave action has little effect owing to the shallowness of the water over the sand banks.

The river, for a distance of 40 miles above New Westminster, is in places bordered by extensive flats, mostly below high-tide, freshet level, which have been formed by the meandering of the river and its tributaries, and by deposition from flood waters. The flats, for the most part, have been carved out of the raised Pleistocene marine clays and delta deposits and form the alluvial flood plain of the river.

PITT LAKE DELTA

An unusual kind of delta is being formed at the lower or south end of Pitt Lake, which drains south by way of Pitt River into the Fraser above New Westminster. The lake is $\frac{1}{2}$ to $2\frac{1}{2}$ miles wide and 15 miles long, and is tidal. During the freshet stage of the Fraser the surface of the water in Pitt River and Pitt Lake is raised several feet above the normal level and falls only slightly with the tides, so that during this time there is very little current into or out of the lake. During the low-water stage, the tides in

the lake have a maximum range of about $3\frac{1}{2}$ feet, and there are strong currents both ways. The delta is being built into the lake at the south end, although the drainage of the lake basin is outward or toward the south. This is the case because the inward, flood-tidal current is stronger than the outward current, because the rise of tide on the flood is more rapid than the fall on the ebb, and the outflow of river water is not great enough to counteract this effect.

The delta is partly submerged and extends about 4 miles into the south end of the lake. The top-set beds are exposed in places at extreme low tide, but are for the most part covered by 3 to 6 feet of water. A single, straight river channel extends through the delta. The delta has advanced along the line of the channel and left unfilled a deep depression on its west side. The fore-set beds are well developed and extend to depths of 20 to 30 fathoms, the slope being in places as much as 30°, but for the most part only about 10°. The lake has a maximum depth near its south end of about 50 fathoms. In the narrow parts near the north end the maximum depth is about 80 fathoms.

CHARACTER OF STRATIFICATION OF THE SEDIMENTS

A number of core samples of bottom deposits in the Strait of Georgia, off the mouth of the Fraser and in Pitt Lake, were obtained by means of a bottom-sampling machine. The machine consisted of a hollow casting, 3 feet long, sharpened at the lower end and fitted at the top with a ball valve which worked automatically. The machine weighed 55 pounds and was operated from a motor boat by means of a sounding machine of the ordinary type. The samples were mounted in plaster of paris and sectioned vertically to show the character of the stratification. A number of the samples are shown in Figures 1 and 2.

The stratification of the top-set beds of the Fraser Delta and alluvial flood-plain deposits differs in different parts of the vertical section. Below the level of mean low tide the top-set beds are composed largely of sand, are for the most part horizontally bedded, but in places are cross-bedded and current-ripple-marked. In places there are thick and thin lenses or beds of silt and clay which

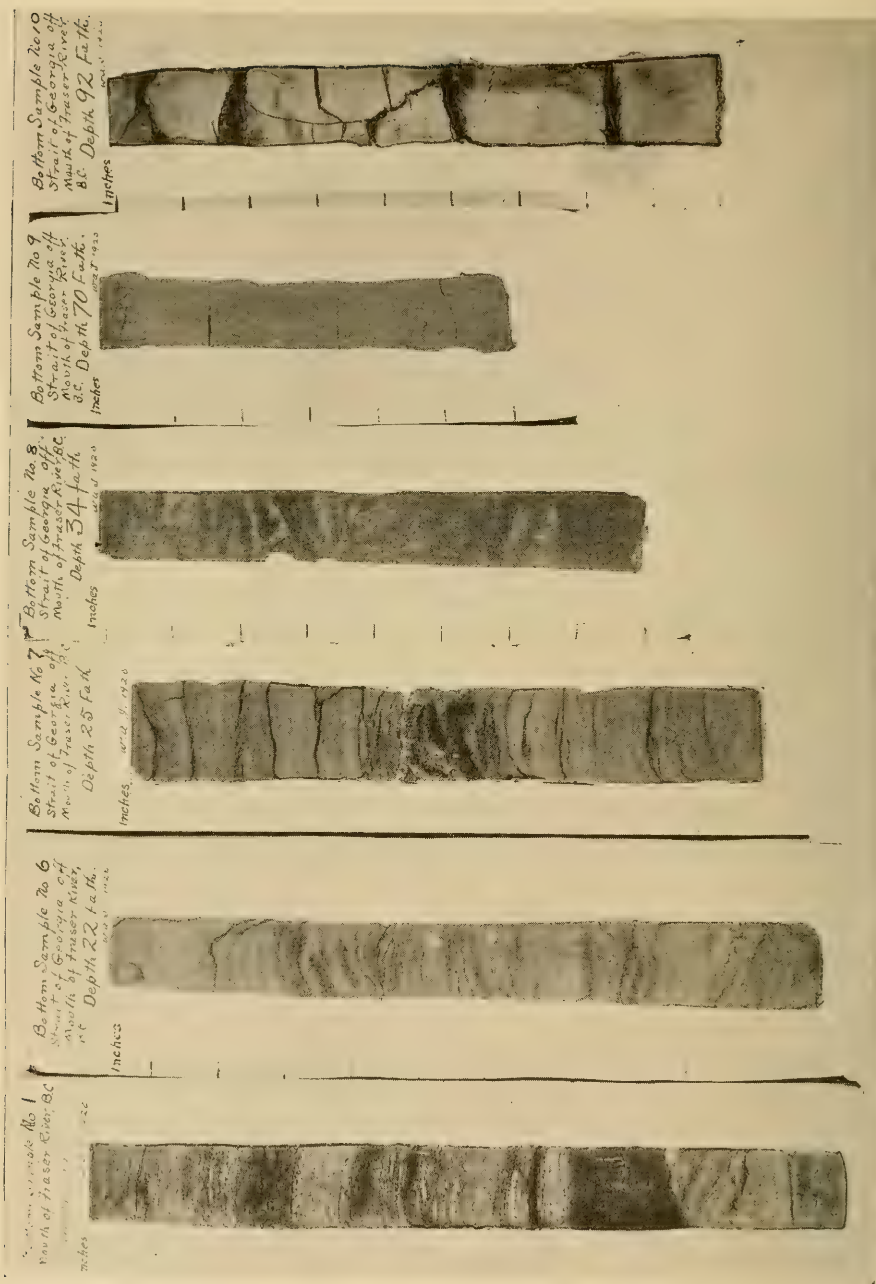

FIG. 1.—Core samples of sediments being formed in the Recent delta of Fraser River, British Columbia, Canada. The samples are mounted in plaster of paris and have been sectioned vertically to show the character of the stratification.

show no definite lamination. The stratification of the sandy beds is in places rendered visible by thin partings of silt and clay. The stratification of the beds in the intertidal zone is very marked, the characteristic feature being a very thin tidal lamination. Bottom sample No. 1, shown in Figure 1, illustrates the character of the stratification of part of the beds in the intertidal zone. The light-colored parts are silty in character and the dark parts are sandy. The seasonal character of these beds is indicated in places by layers of vegetable matter, and in other places by the different character of the laminae formed during the freshet stage of the river, from those formed during the low-water stage. During the freshet the water holds in suspension considerable quantities of silt, and during the low-water stage it is nearly clear. Hence the laminae formed during the freshet are largely silt, and those formed during the low-water stage are largely fine sand. The tidal laminae average possibly 15 to 20 to the inch. The seasonal layers average about 5 or 6 to the foot. But as contemporaneous erosion and deposition are constantly going on, any one section gives a very incomplete record of either the tidal laminae or seasonal layers.

The stratification of the alluvial flood-plain deposits differs from that of the tidal flood-plain deposits because of the fact that during the freshet the surface of the part of the river above New Westminster is raised above the normal level and falls very little with the tides. Hence, during the freshet, a single layer of silt, which may be as much as $\frac{1}{2}$ inch in thickness, is deposited on the alluvial flood plain. Neither the tidal nor the alluvial flood-plain laminae show any marked gradation upward from coarse to fine particles in the individual laminae.

The character of the stratification in the fore-set beds of the Fraser Delta is indicated approximately in samples Nos. 6, 7, and 8 shown in Figure 1. The beds are composed of a mixture of fine sand (0.1 to 0.05 mm.), silt (0.05 to 0.005 mm.), and clay (less than 0.005 mm.). They are, for the most part, thinly laminated, in a somewhat similar manner to the tidal flood-plain deposits. In places the lamination is even, in other places it is markedly irregular, and cross-bedding as well as inclined bedding occurs. The lamination is tidal in character, but is the result of the com-

bined effects of flocculation in sea water, river and tidal currents, and slack water. A leaf bed is shown in sample No. 7 at about mid-length. As it is known from a comparison of soundings made in 1859 and shown on the 1860 chart with those made in 1919 by the Hydrographic Survey of Canada that sedimentation takes place in the fore-set beds, at the points where the samples were taken, at the average rate of about 20 feet per year, it is obvious that the samples would not show evidence of seasonal banding. It is known that coarse material is deposited off the mouth of the river during the freshet, and that this is overlain by finer materials deposited during the low-water stage. Hence the bedding probably has in places a seasonal character, but the annual layers vary in thickness, in different parts of the delta front, from a few inches or even less to as much as 50 feet.

Bottom samples Nos. 9 and 10, shown in Figure 1, are from the fine-grained bottom-set beds of the delta, in the Strait of Georgia. Sample No. 9, from a depth of 70 fathoms, is largely silt, and sample No. 10, from a depth of 92 fathoms, is largely clay, which, because of excessive shrinkage in drying, is badly cracked. The samples as mounted and shown in the figures are smaller in size than in the original state because of compression and shrinkage in drying. Sample No. 10 is most compressed, and, judging by the depth of penetration indicated by the mark left on the outside of the sampling machine, is one-half to two-thirds of its original length. The other samples are more nearly representative of the original thicknesses.

A marked feature of the bottom samples from the fine-grained bottom-set beds is the absence of any trace of lamination either in the beds composed of silt with a mixture of very fine sand, or in the beds composed for the most part of clay. The lack of lamination is due to the well-known effects of flocculation in sea water, which causes the fine silt and clay particles in suspension in the river water to settle to the bottom together when flocculation takes place as the result of the mixing of the two waters. In places also very fine sand settles to the bottom along with the silt and clay. Hence, in the case of the fine-grained materials deposited in sea water, there is a lack of sorting and no definite lamination,

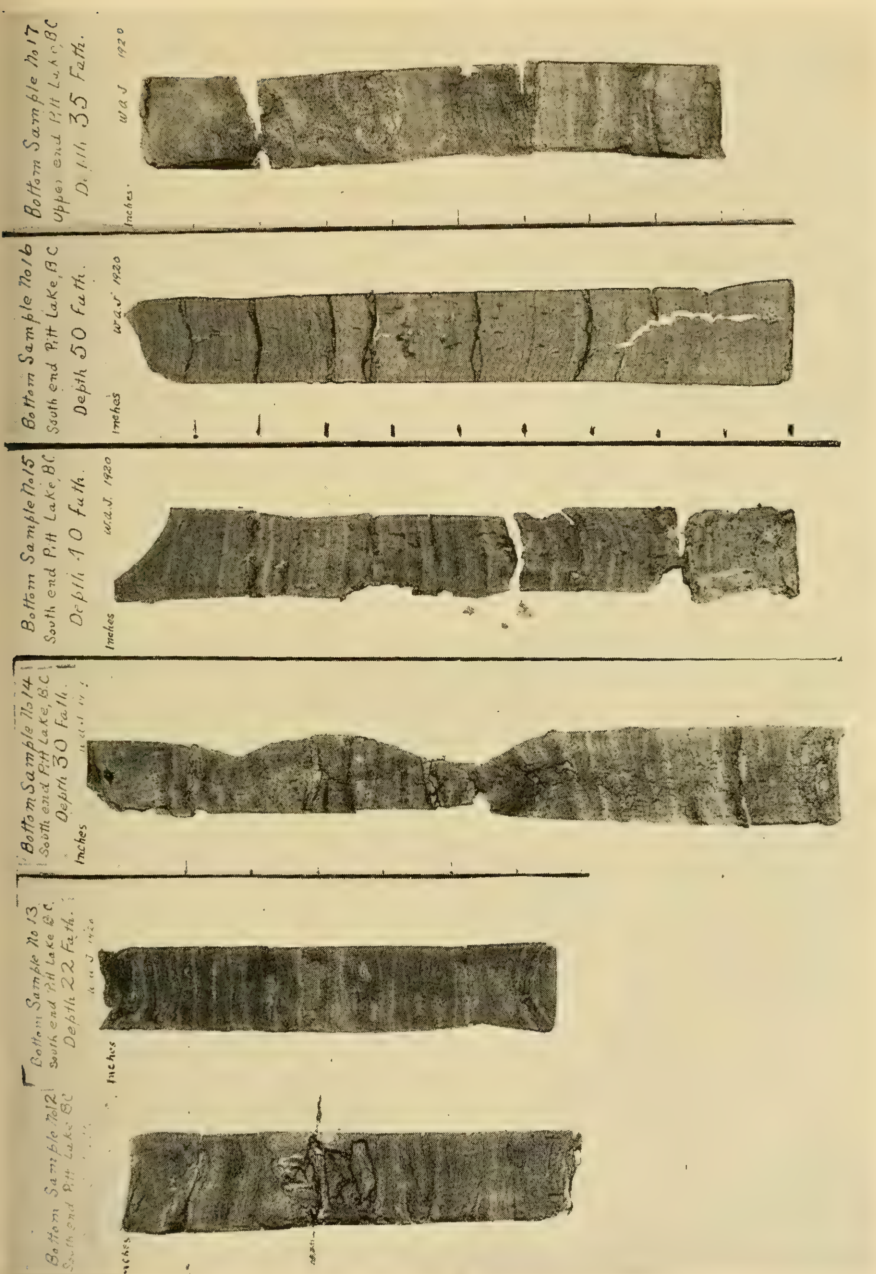

FIG. 2.—Core samples of sediments being formed in Pitt Lake, British Columbia, Canada. The samples are mounted in plaster of paris and have been sectioned vertically to show the character of the stratification.

and the beds are probably thick and massive. As the samples from the bottom-set beds were taken at points where sedimentation is taking place at the rate of at least 1 foot per year, they cannot be taken as criteria of the presence or absence of seasonal banding. It is possible that in places the bedding is seasonal in character, for coarser material is carried out into the strait during the freshet than during the low-water stage of the river.

Samples from the bottom of Pitt Lake are shown in Figure 2. Sample No. 12 is from the submerged top-set beds, samples Nos. 13 and 14 are from the inclined fore-set beds, and samples Nos. 15 and 16 are from the bottom-set beds of the delta at the south end of the lake. Sample No. 17 is from the bottom-set beds of the delta formed by inflowing streams at the north end of the lake.

The character of the stratification of the deposits formed in the tidal fresh-water body differs in several ways from that of the deposits formed in salt water in the Strait of Georgia. Tidal laminae are shown to some extent in all the samples from Pitt Lake. They are exceedingly fine, being in places as many as 100 to the inch. The bedding of the fore-set beds is much more even than that of the fore-set beds of the Fraser Delta, apparently because of the absence of tidal currents along the front of the delta. Samples Nos. 13, 14, and 15 (Fig. 2) were taken at the south end of the lake near the subaqueous front of the delta. They all show a fairly regular recurrence of silty layers (light-colored) separated by sandy layers (dark colored). This banding is probably tidal in character and may be explained as follows. There are two tides daily in Pitt Lake, but one is so small that as a rule the current is not reversed; so that there is nearly always only one period of outflow and one of inflow each day. Large tides occur twice a month near the times of maximum declination of the moon, and small tides occur near the times when the moon is over the equator. The inward current is greater at the period of large tides than at that of small tides. During the times of large tides sand tends to be deposited, and during the times of small tides silt tends to be deposited. The sandy bands separating the silty bands are very thinly laminated and in places contain eight or ten laminae. The silty bands also are in places thinly

laminated, but not so definitely as the sandy bands. The rate of deposition in the Pitt Lake Delta is not definitely known, but probably is very small, for a comparison of a number of soundings taken in 1920 with those taken in 1860 shows no great difference. The soundings taken at the point, about 1 mile from the front of the delta, where sample No. 16 was obtained, showed that deposition had taken place to a depth of 5 to 10 feet during the past 60 years, or at the rate of 1 or 2 inches a year. The rate of deposition near the front of the delta is probably much greater. The beds probably show therefore both tidal lamination and tidal banding. They apparently do not show seasonal banding. From the fact that there is very little current in the entrance to Pitt Lake during parts of May, June, and July when the Fraser is in flood, it might be expected that this period would be indicated in the bottom samples by a thick layer of silt. During this period, however, the turbid water of the Fraser does not enter Pitt Lake to any extent and the lake water is nearly clear.

Bottom sample No. 16, taken at a depth of 50 fathoms, is from the bottom-set beds of the delta, in the deepest part of Pitt Lake, near the south end. It is composed of silt and clay and differs markedly in the character of its stratification from the fine-grained samples from the bottom-set beds of the Fraser Delta in the Strait of Georgia in that it is thinly and gradationally laminated. The lamination is probably due to tidal action and to the absence of flocculation of the fine material in suspension in the fresh water, which permits the silt and clay to settle to the bottom at different rates.

Bottom sample No. 17, taken at a depth of 35 fathoms, is from the bottom-set beds or from near the contact of the fore-set bottom-set beds of the delta at the north end of Pitt Lake. It shows in places a tidal lamination and probably also a seasonal banding. There is a fairly regular recurrence of silty layers ½ to 1 inch, separated by sandy layers 1 to 2 inches thick. The silty layers were probably deposited during the freshet when the surface of the lake did not rise or fall appreciably with the tides, and the sandy layers during the periods when the lake was affected by the tides; for at ebb tide the currents in the streams flowing through the

delta at the north end of the lake are greatly increased. This appears to be borne out by the fact that in places the sandy layers are thinly laminated.

SUMMARY OF CONCLUSIONS

The tidal flood-plain deposits of the Fraser River are characterized by a very thin lamination which is tidal in origin. The seasonal character of the bedding is shown in places by layers of vegetable material and in other places by alternations of silty layers and sandy layers, both of which show tidal lamination.

The alluvial flood-plain deposits of the Fraser are characterized by seasonal layers of silt and vegetable material.

Neither the tidal nor the alluvial flood-plain deposits show to any marked extent gradational lamination.

The fore-set beds of the Fraser Delta, deposited in sea water, are characterized by a thin lamination which is the result of the combined action of flocculation in sea water, river and tidal currents, and slack water. The beds have in places marked cross-bedding as well as inclined bedding. The fine-grained bottom-set beds are thick and without lamination, because of the effect of flocculation in sea water.

The Pitt Lake Delta deposits formed at the south end of Pitt Lake (a tidal fresh-water lake) are characterized by a very thin lamination and by a banding, both of which are probably tidal in origin. The fine-grained bottom-set beds have a very thin and gradational lamination, which is due to tidal action and to the absence of flocculation in fresh water. They show no definite evidence of seasonal banding. The deposits now forming in the delta at the north end of Pitt Lake have a tidal lamination and probably also a seasonal banding.

A conclusion which may be drawn from the fact that the fine-grained sediments deposited in salt water are not laminated, because of the effects of flocculation, while those formed in fresh water are, is that fine-grained sediments which are evenly and gradationally laminated are fresh-water sediments in origin or, if marine in origin, are glacial; for it is probable that sea water would

be sufficiently dilute to prevent flocculation and hence to permit of lamination of the sediments only at times when and in places where large volumes of water from melting ice sheets were being poured into the sea. A possible exception might occur in places where large volumes of river water are being poured into an estuary or into a nearly land-locked part of the sea; but flocculation takes place in the Strait of Georgia in spite of the large volume of fresh water brought down by the Fraser, and where the density of the surface sea water is only 1.010, as compared with the density of normal sea water which at 17.5° C. is 1.027.

THE STRUCTURAL RELATION OF THE PURCELL RANGE AND THE ROCKY MOUNTAINS OF CANADA

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It has been found repeatedly, in recent years, that on the flanks of many elongated mountain ranges there are thrust faults dipping in under the range. In the absence of these faults, overturned folds, with their axial planes dipping into the range, and indipping slaty cleavage are common. Partly from observation of this sort, Dr. R. T. Chamberlin developed his hypothesis of the wedge-shaped zones of deformation in mountain building.[1] With this idea in mind, I attempted to determine whether the Rocky Mountain trench, a long, narrow depression between two mountain ranges, would show a connection with this type of structure.

This great valley has a length of about 800 miles. It starts somewhat south of the boundary line between the United States and Canada and runs in almost a straight line to the northwest between the Rocky Mountains on the east and a succession of ranges on the west. From what is known about the trench it has been estimated to have an average width from wall to wall of 5 miles. The portion of the trench which I studied was from Gateway, Montana, at the boundary line, to Golden, British Columbia, 180 miles to the north. Study of the trench has been hitherto quite limited. Dr. Daly's section at the 49th parallel[2] crosses the trench, Dr. Schofield's "Cranbrook Area"[3] borders the west side of it for about 60 miles, and the section along the main line of the Canadian Pacific across the Cordillera, made by Allen and Daly,[4] crosses it about 200 miles north of the boundary. Others have made rapid reconnaissances of the trench.

[1] R. T. Chamberlin, *Jour. Geol.*, Vol. XVIII (1910), p. 228.

[2] R. A. Daly, *Geol. Surv. Can. Mem. 38* (1912).

[3] S. J. Schofield, *Geol. Surv. Can. Mem. 68* (1915).

[4] *Guidebook No. 8*, Congrès Géologique International, 1913.

In the 180 miles which I studied, there are two distinct geographic provinces. In the northern province, which extends as far south as Canal Flats, the trench is drained by the Columbia River which has its source in Columbia Lake just north of the Flats. The valley is narrow, for the most part not more than 3 or 4 miles wide. In part of this northern zone there is a wide valley west of and parallel to the Columbia Valley, which joins the trench at both ends and is only separated from it by a narrow ridge, broken in one place. South of Canal Flats the valley is drained by the Kootenay River, which comes into the trench from the east and flows south. In this portion the trench becomes much wider till it reaches its maximum width of 16 miles at Fort Steele. South of there it contracts rapidly to 5 miles at Bull River, but widens again at Elko and at Gateway.

From what could be deciphered from the stratigraphy, it was found that there are two principal series of rocks represented. One is a great succession of limestones ranging from the upper Cambrian to the Mississippian, but with rather large stratigraphic disconformities. The other series is dominantly clastic, consisting chiefly of various metamorphic phases of sandstone, shale, and conglomerate. It has recently been determined, in at least some cases, to be Cambrian, but probably includes much pre-Cambrian. Probably its age overlaps somewhat that of the limestone series. As shown on the map (Fig. 1), this last series makes up most of the west side of the trench in the northern zone, while the limestones are on the east side and occasionally overlap to the west side. South of Canal Flats the limestone series retreats into the Rocky Mountains, and the clastic series crosses the trench, and occupies a zone about 12 miles wide on the east side. Farther south, between Bull River and Gateway, the limestone series again appears in various hillocks in the trench and in narrow zones along its sides.

Structurally the trench has hitherto been considered as a sort of Graben[1] or at least the product of normal faulting.[2] The results

[1] R. A. Daly, *Geol. Surv. Can. Mem. 38*, p. 600.

[2] S. J. Schofield, "The Origin of the Rocky Mountain Trench," *Trans. Roy. Soc. Can.*, Sec. 4 (1920), pp. 73–81.

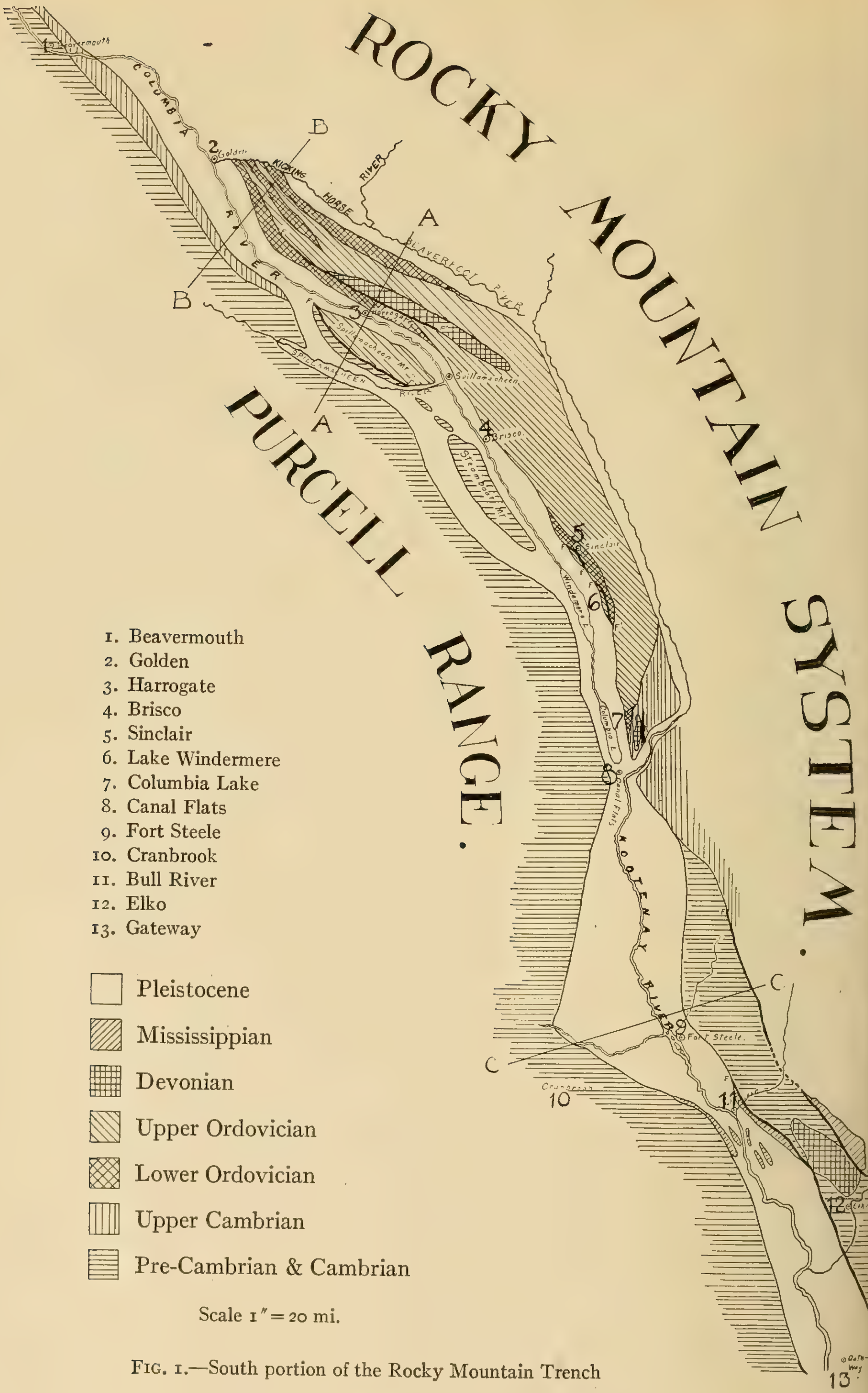

FIG. 1.—South portion of the Rocky Mountain Trench

of my study do not harmonize with this view. The structure should be considered in three divisions.

1. *The northern part.*—In the northern part, the trench is certainly defined by structural features. While the structure varies considerably, there are some features which hold for the entire distance. There is, for example, intense folding on both sides of the trench. The axes of the folds in most cases dip away from the trench, and in places are overturned (Fig. 2).

Most of the faults are thrust faults. On the west side most of these have west-dipping fault planes. On the east, most of the

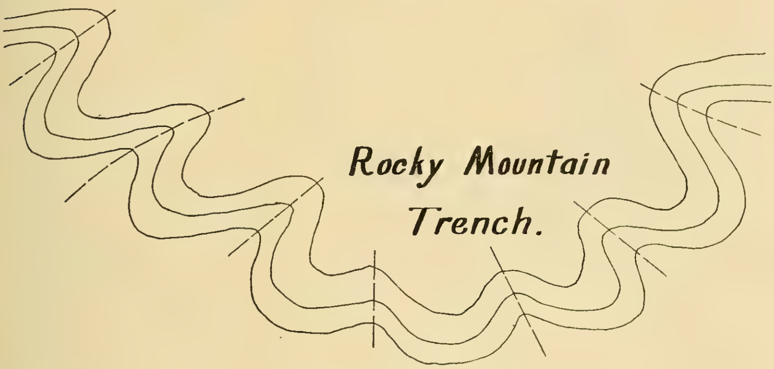

FIG. 2.—Ideal section of folding

thrusts have east-dipping planes. There is a very large thrust fault, which either borders or is found in the trench from Canal Flats almost to Parsons. This fault causes the semimetamorphic series of pre-Cambrian and early Cambrian age to be thrust over against the topmost beds of a thick Ordovician series on the east. At Harrogate (Fig. 3) there are two west-dripping thrust faults each with a displacement of more than 6,000 feet. This great fault probably does not exist north of Parsons. At Beavermouth, 25 miles northwest of Golden, Daly considered that the upper Cambrian-Ordovician series on the east was separated from the Cougar Quartzite on the west by a normal fault of 15,000 feet displacement. In a section in Canyon Creek (Fig. 4) near Golden, the same formations were found as those occurring on the two sides of the fault at Beavermouth, and here there is no fault and the formations follow each other in normal stratigraphic succession.

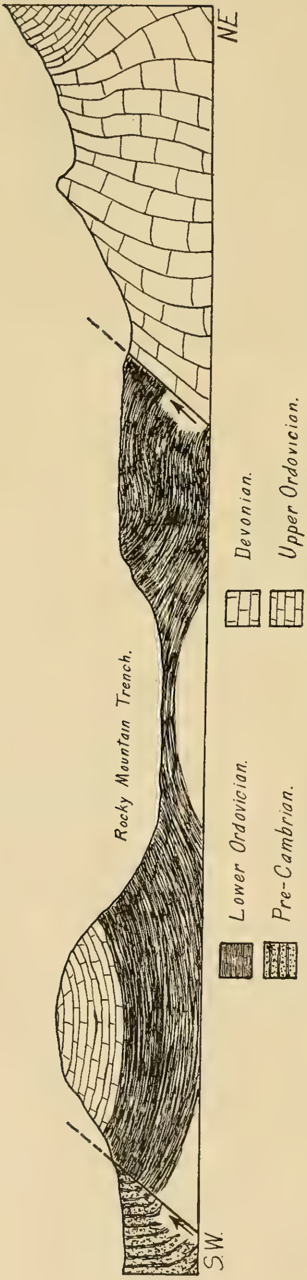

FIG. 3.—Section at Harrogate (through $A—A$, Fig. 1). Scale: 1 inch = 1.06 miles

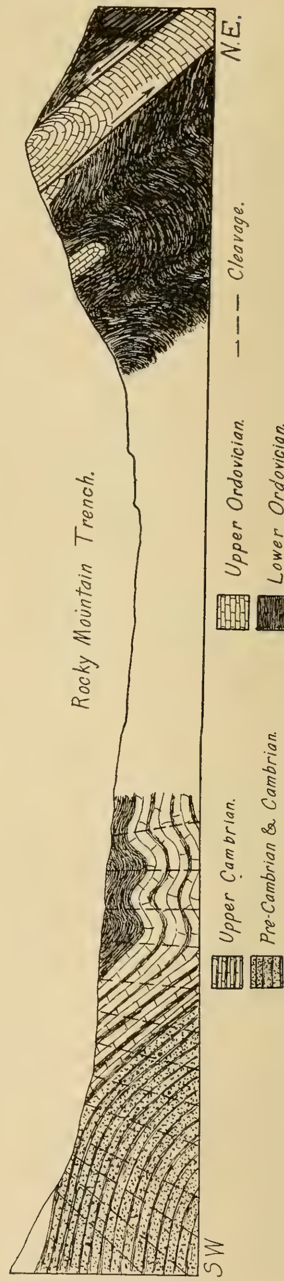

FIG. 4.—Section at Canyon Creek (through $B—B$ Fig. 1). Scale: 1 inch = 1.2 miles

At Beavermouth there is a wide zone separating the two series in question, and the fault was inferred entirely on lithological grounds. It seems unlikely that such a fault exists. As will be seen from the section, thrust-faulting on the east is important in this region, which is rather significant in view of the dying out of the west-dipping thrust faults.

In the southern portion of this northern zone there are cases on the east side of the trench where there are intersecting east- and west-dipping thrust faults. In all such cases the west-dipping thrusts cut those from the east. There is an interesting example

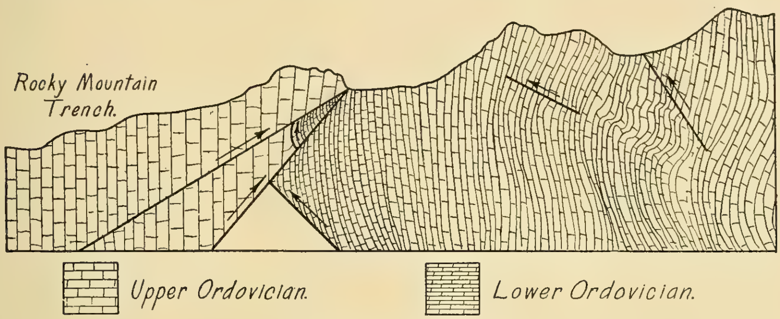

Fig. 5.—Section at Sinclair

of this at Sinclair Springs (Fig. 5). To the east the west-dipping thrust faults always become less conspicuous, and finally die out. At Brisco an east-dipping thrust fault was found on the west side of the trench. Thus there is considerable intersection of the east- and west-dipping thrust faults.

If the general rule for thrust faults is to have dips of much less than 45°, then these faults are exceptional since their dips average about 50° and in some cases are as high as 70°. This is in contrast to the low dips of the thrust faults on the east side of the Rockies in the northern United States and Canada. Experiments, on folding and faulting, which I have made, show that faults which develop at the intersection of two folds may have dips which exceed 45° due to the upward relief being much easier than the lateral. The faults developing between two separate mountain ranges might be subjected to the same influences.

The age of the faulting is not known definitely, but there are several factors bearing on the age, which should be mentioned. In the first place the faulting must have been subsequent to most of the folding in the Rocky Mountains, because in almost no instances are the fault planes involved in the severe folding found on the east side of the trench. The folding of the Rockies is thought to have been mostly during the Laramide revolution. In several cases thrust faults of very great throw were found to exist in such a location that the upthrow side of the thrust is in the valley, while the downthrow side forms the mountain wall (Fig. 3). This feature was found in so many cases that it is obvious that faulting does not directly control the topography. Therefore this faulting must be old. It seems probable that it took place in early Eocene times, at the close of the Laramide deformation. If the overthrusts on the east side of the Rockies are contemporaneous with those on the west, the great amount of subsequent erosion lends some weight to the problem of the age of the Lewis overthrust, which has been considered either early Eocene or Miocene.[1]

The slaty cleavage found in the vicinity of the trench in this section is very constant in character in that it persistently dips to the east on the east side of the trench, while on the west side it dips to the west. Up Canyon Creek, where the section was almost uninterrupted, the cleavage, as shown by the dotted lines (Fig. 4), dips to the west in the Purcell Mountains, becomes gradually vertical toward the middle of the trench, and farther east dips at high angles to the east. Across the trench the cleavage dips to the east at lower angles.

Thus the folding, the thrust-fault system, and the slaty cleavage all point toward the indipping structures and are evidence in favor of Chamberlin's hypothesis of the wedge-shaped deformation masses formed in mountain-building. Here in the trench two intersecting wedges occur, one the Rocky Mountain and the other the Purcell-Selkirk system. The great overthrusts on the east side of the Rockies, such as the Lewis thrust and the Cascade Mountain

[1] B. Willis, *Bull. Geol. Soc. of America*, Vol. XIII (1902), p. 333; R. A. Daly, *Geol. Surv. Can. Mem. 38*, pp. 90–95.

thrust, are examples of indipping structure on the other side of the Rocky Mountain wedge.

The cause of this valley in the northern section is partly the zone of weakness produced by the intersection of such a large number of fault planes, causing erosion to be more rapid here than elsewhere. Also the type of folding on the sides of the trench produced a depression between (Fig. 2).

South of Canal Flats the zone which separates the structure of the Rocky Mountains from the Purcell Range leaves the trench, and swings to the east. This zone does not die out, but appears in the Hughes Range of the Rockies some 12 miles from the trench. It was traced as far south as Elko. In at least two places, this zone has overthrust faults from the west. Fifteen miles up into the

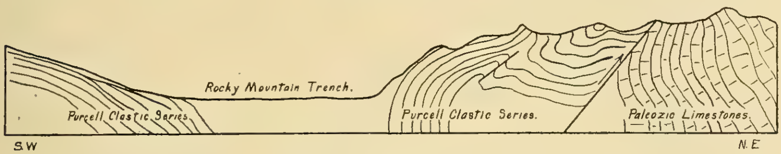

FIG. 6.—Section at Fort Steele (through *C—C*, Fig. 1). Scale: 1 inch = 14.63 miles.

Rockies from Fort Steele, there is an overthrust with a throw of several thousand feet (Fig. 6). No valley exists along this fault, which shows that the faulting does not always control topography.

2. *The central part.*—From Canal Flats to Bull River the trench does not follow structural lines, neither in regard to the strike of the bordering formations, which is roughly parallel on both sides, nor, so far as could be found, in regard to the faults. The conclusion to be drawn from this point is that this part of the trench was developed by a stream flowing on an old erosion surface which was flat enough to allow the river to develop its course independently of structure.

This conclusion is strengthened by several factors. To begin with, the Purcell Range is thought by Schofield[1] to have been deformed in the Jurassic and peneplained in the Cretaceous, and at this time to have developed many valleys out of accord with the structure developed in the Jurassic mountain-building. After the

[1] S. J. Schofield, *Geol. Surv. Can. Mem. 76*, pp. 101–2.

uplift of the Purcell Range, these streams maintained their courses and developed antecedent drainage. That the old Purcell Range existed on both sides of the trench in this zone is evidenced by finding the typical Purcell strike on the east as well as on the west side of the trench. Also the Purcell series (pre-Cambrian) is present on both sides of the trench in this zone.[1]

The great width of this portion of the valley, 16 miles, is out of accord with the rest of the trench, which might be explained by greater age. Also there was found a continuation of the antecedent portion of the trench up into the Purcells leaving the trench in the vicinity of Cranbrook, and it is just south of here that the trench is found to be again connected with structure.

3. *The southern part.*—The southern structural unit extends from Bull River down to Gateway. In this zone there is a thrust fault on the east side of the trench which causes the Mississippian, or in some cases the Devonian, to be brought into contact with the Galton series, partly Cambrian and partly pre-Cambrian,[2] on the east. Large disconformities in this general region make it difficult to estimate the displacement of the fault. It probably is not more than 2,000 or 3,000 feet north of Elko, but at the boundary line it was estimated by Daly[3] to be as much as 10,000 feet. Ten miles south of Bull River it virtually dies out. Here the Devonian limestone comes down from the mountains into contact with the Mississippian in the valley.

This fault, which appears to limit the east side of the trench from Bull River to Gateway, was considered to be a normal fault by both Daly[4] and Schofield.[5] The writer has no definite proof that this is not the case, but there are several facts which suggest that it is a thrust fault. In the first place the trace of the fault plane at Gateway was followed with considerable certainty for several miles, and it was found that the fault plane curved decidedly up a tributary valley to the east (Fig. 7). This, of course, suggests an east-

[1] S. J. Schofield, "The Origin of the Rocky Mountain Trench," *Trans. Roy. Soc. Can.* (1920). P. 76.

[2] S. J. Schofield, *Science*, Vol. LIV, p. 666.

[3] R. A. Daly, *Geol. Surv. Can. Mem. 38*, p. 118.

[4] *Ibid.*

[5] S. J. Schofield, "The Origin of the Rocky Mountain Trench," *Trans. Roy. Soc. Can.* (1920), p. 76.

dipping fault plane. As the upthrow is on the east, the relation is that of a thrust fault.

Also along the eastern wall south of Bull River there is a place where the Mississippian appears to dip under the Galton series on the east. The common occurrence of the east-dipping thrust faults in the northern zone on the east side of the trench suggests the probability of this fault being one of the thrust type. It was thought by Dawson[1] that the fault continued north of Bull River because of a depression along the east side of the valley. The

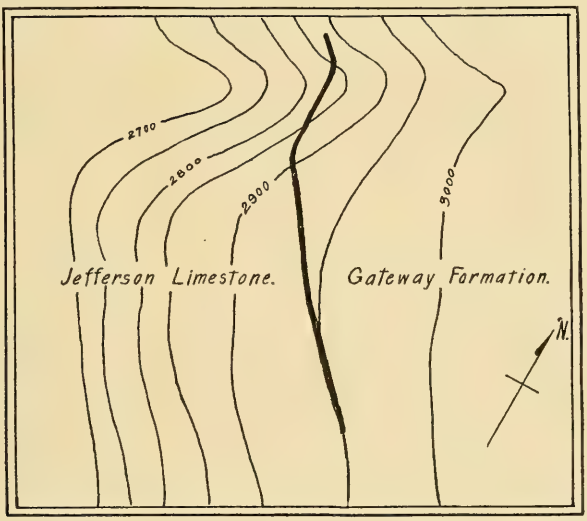

FIG. 7.—Sketch contour map showing trace of fault east of Gateway

writer considers that this depression is one of many instances of drainage along the flanks of the retreating valley glaciers. The valley in this southern section was probably originally defined by this fault plane, and subsequent erosion has broadened the valley chiefly to the west.

In conclusion, the Rocky Mountain trench does not appear to be the unit in its development and structure that it has been thought to be by Daly and Schofield. It appears instead to have been produced partly by normal erosion, partly by erosion along lines of structural weakness, and partly by the escarpment of a fault. Even in this last instance the faulting is probably of the thrust rather than of the normal type.

[1] G. M. Dawson, *Geol. Surv. Can., Ann. Rept.* (1885), p. 190B.

ASPECTS OF ONTOGENY IN THE STUDY OF AMMONITE EVOLUTION

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It is well known that the development of an individual generally recapitulates to some extent the stages passed through during the evolution of its ancestors, or in other words, that "ontogeny repeats phylogeny." In the paleontological work of the last quarter of a century this principle of recapitulation has frequently been used in determining the relationships of fossils, and its general truth has been demonstrated among many groups of Invertebrates; for example, by Mr. R. G. Carruthers and others among the Rugose corals,[1] by Professor Grabau among the Gastropods,[2] and by numerous workers, particularly Mr. S. S. Buckman, among the Ammonites.[3]

That ontogeny is not always merely a recapitulation of phylogeny, however, has been recognized by zoölogists for many years; the development is often modified to fit the embryo for a special mode of life, as in many modern Arthropods, so that ancestral stages are obscured to a greater or less extent. In other cases on account of the individual hurrying through its development in order to attain maturity as early as possible, certain phylogenetic stages are "skipped" in development.

Numerous paleontologists have recognized the importance of this skipping of stages in development; Mr. S. S. Buckman dealt with it some years ago and has pointed out several examples.[4]

[1] See, for instance, R. G. Carruthers, "The Evolution of *Zaphrensis delansuei*," *Quart. Jour. Geol. Soc.*, Vol. LXVI (1910), p. 523.

[2] A. W. Grabau, "Phylogeny of *Fusus* and Its Allies," *Smithsonian Misc. Coll.*, No. 1417 (1904), pl. xviii, fig. 2.

[3] See, for instance, "Yorkshire Type Ammonites." Introduction to Vol. I (1909–12).

[4] S. S. Buckman, "Monograph of the Inferior Oölite Ammonites," *Palaeont. Soc.*, p. 289.

More recently, he proposed to call it by the name of "saltative palingenesis";[1] Dr. W. D. Lang suggested the simpler term "lipogenesis"[2] but as this term may convey a wrong idea of the skipping of stages *in ontogeny*, Mr. Buckman has now proposed the term "lipopalingenesis."[3]

The study of fossil lineages affords a ready means of investigating the various ways in which the skipping of stages has been brought about. This is particularly true in the case of ammonites, among which it is comparatively easy to study the ontogeny of successive members of a lineage.

From such studies it appears that there are several slightly different ways in which phylogenetic stages come to be skipped in the development of later members of a series. The object in this article is to draw attention to some of these aspects of lipopalingenesis.

THE OMISSION OF EARLIER CHARACTERS

In many cases the characters omitted are those of the earliest ancestors, and the "skipping" means rather the omission of the earliest phylogenetic stages. This occurs as a direct result of the acceleration of development (tachygenesis). A simple example may be found in the evolution of the Ammonoids or Nautiloids. It is generally accepted that these have evolved from straight *Orthoceras*-like forms, through curved *Cyrtoceras*-like forms, to closely coiled forms like *Nautilus* itself. Now it may be admitted that the *Orthoceras*-like stage is repeated in an abbreviated manner, in the early portion of the *Cyrtoceras* form, but in succeeding members of the series this stage becomes progressively shorter, and in Mesozoic Ammonites it can scarcely be said to be represented at all.

In most cases of lipopalingenesis the stage or character omitted is not the most primitive.[4] This is illustrated by the skipping of

[1] S. S. Buckman, "Yorkshire Type Ammonites," Vol. I (1909–12).

[2] W. D. Lang, *Proc. Geol. Assoc.*, Vol. XXX (1919), p. 60.

[3] S. S. Buckman, "Type Ammonites," Vol. III (1920), p. 11.

[4] It should be noted that in the case just given, the skipping of the *Orthoceras* stage merely represents the skipping of the earliest *skeletal* stage.

certain ornament stages in the development of Ammonites. The normal order of appearance of ornamentation in Ammonites, as in many other groups is (*a*) striae, (*b*) costae, (*c*) tubercles. But although this order is followed in phylogeny almost invariably, and often, in a general way, in ontogeny, in certain "accelerated" members of phylogenetic series the striate and occasionally also the costate stages are omitted in development, the tuberculate stage having been accelerated so that it directly succeeds the smooth stage. The smooth embryonic stage of an Ammonite may be restricted to the first few whorls, but however accelerated the specimen, the inner whorls appear to be always smooth; the smooth stage is never skipped, while the later costate or striate stages may be.[1]

Similar examples may be found among the Brachiopods and Lamellibranchs. Dr. Lang points out to me that in certain advanced corals twelve septa appear simultaneously in the embryo, the early phylogenetic stages, with fewer septa, being skipped.[2]

THE OMISSION OF COMPARATIVELY LATE CHARACTERS

A more interesting form of lipopalingenesis is illustrated by certain Ammonite groups; perhaps the clearest example is to be found in the evolution of the Liparoceratidae.[3] Slender "capricorn" Ammonites of this family evolve through intermediate stages to stout bituberculate forms, but the ontogeny of the latter shows no stage in any way comparable with their immediate ancestors, the slender capricorn forms. This skipping of the slender-whorled stage is represented diagrammatically in Figure 1, which shows sections of three Ammonites typical of (*A*) the slender capricorn forms, (*B*) the intermediate forms, (*C*) the stout forms, from one genetic series. In the ontogeny of the capricorn form the depressed early whorls (i and ii) pass into round whorls (iii–v); in (*B*) the stage with depressed whorls is shortened (by acceleration of the slender whorl stage) but the latest whorls are stouter than in the adult of *A*. This stout form of whorl is more characteristic of *C*, and has

[1] In certain accelerated Gastropods striae may be present on the protoconch and the smooth stage is there omitted (Grabau, *op. cit.*).

[2] See *Geological Magazine*, N.S., Dec. V, Vol. IX (1912), p. 557.

[3] A. E. Trueman, "The Evolution of the Liparoceratidae," *Quart. Jour. Geol. Soc.*, Vol. LXXIV (1919), pp. 2, 7.

been accelerated; since the depressed *early* whorls are also prolonged the slender whorl stage is skipped entirely in the development of this form.

The reason for this skipping is perhaps best appreciated when it is remembered that the Ammonite *C* was thus able to produce the adult form directly, instead of developing from stout (embryo) to slender (youth) and back to stout (adult). The tendency to omit in development the stage which appears unnecessary for the production of the adult form would perhaps be expected; the most interesting fact is that this skipping is accomplished not simply by the acceleration of the stout form of whorl but partly by an *apparent* retardation of the early characters, notwithstanding that the series is distinctly progressive.

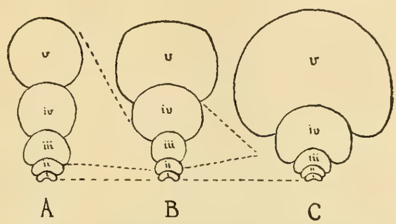

FIG. 1.—Sections to show the changes of whorl-shape in three ammonites from a single lineage of the Family Liparoceratidae:

A, a slender capricorn ammonite.

C, an involute stout ammonite.

B, a form intermediate between these two.

Without discussing here the biological interest of these observations, it is perhaps not out of place to notice that if lipopalingenesis is of frequent occurrence, the tracing of phylogeny from ontogenetic evidence is not so easy as has been thought by some workers. It is comparatively easy to follow cases of skipping of stages when an early phylogenetic stage is omitted, but in cases like the one just described, where the characters omitted are some of the more advanced, there is obviously much difficulty in tracing descent from developmental evidence alone. In such cases, descent can only be proved by the finding of series of intermediate forms connecting the various species.

A NEW PHYTOSAUR FROM THE TRIAS OF ARIZONA

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Among the vertebrate remains from the Triassic of the western states no other group is so abundantly represented as the Phytosauria. Relatively abundant as fossils of this group are, however, there is much to be learned of each of the several distinct types that have been described. For the most part it is the skull that is available for study, but even this is imperfectly known.

Some time ago the writer described a well-preserved phytosaur skull from Arizona, now in the geological museum of the University of Wisconsin. This skull was considered a new form and was made the type of the genus *Machaeroprosopus*.[1] While several of the doubtful details of the phytosaurian skull were made known by the study of the specimen, especially the relations of the bones of the posterior side, the palate, as is usually the case, was left in doubt.

Through the kindness of the University of Chicago the writer was permitted some time ago to study a phytosaur skull in the collections of Walker Museum; a skull very similar to the University of Wisconsin specimen in many points. The study of this material has made evident several pointed suggestions especially concerning the structure of the palate.

The specimen herein described is No. 396 of the Walker Museum Vertebrate Paleontology Collections. It is the gift of Professor J. E. Anderson, formerly of the School of Mines, at Socorro New, Mexico. The name of the collector is unknown and the exact locality has not been recorded. However, the skull is known to

[1] M. G. Mehl, "New or Little-known Reptiles from the Trias of Arizona and New Mexico, with Notes on the Fossil-Bearing Horizons near Wingate, New Mexico," *Bull. University of Oklahoma*, New Series No. 103, University Studies Series No. 5, 1916, pp. 5–24.

have come from the Triassic of Guadaloupe County, near Santa Rosa, New Mexico.

The material collected consists of a few large, well-preserved pieces of bone representing a fairly complete skull (Fig. 1). In the skilful hands of Paul C. Miller the missing portions have been restored in plaster and the major features are almost as certainly determined as though all the fragments had been collected. On both the dorsal and the ventral sides the skull is complete along the median line save for the occipital condyle proper. On the right side the jugal, except for the portion that forms the posterior border of the antorbital fenestra and the process that takes part in the border of the orbit, is missing, as is the quadratojugal, the squamosal, and all but the anterior end of the postorbital. On this side, too, the outer end of the paroccipital and the quadratopterygoid bar are missing. On the left side the missing portions are much the same as on the right, except that the restoration extends farther forward. On the left side the posterior end of the jugal and all of the quadratojugal are preserved.

The skull (Fig. 1) is large, about 865 mm. long, and massive. It is a crested form of the "broken outline" type. From an oval cross-

Fig. 1.—*Machaeroprosopus andersoni*, side view of restored skull, slightly over one-sixth natural size. Sutures indicated by broken lines cannot be determined.

section just behind the expanded and abruptly downturned tip, the rostrum gradually assumes an A-shaped cross-section. Back from the tip for a distance of about 293 mm. the rostrum does not increase in depth materially. At this point, however, the outline of the crest bends in a pronounced curve upward for a short distance and then extends in an essentially straight line up to the anterior border of the nares, 512 mm. from the tip of the rostrum. As the crest approaches the nares after the abrupt rise, it loses much of its angular cross-section.

The narial "hump," while actually rising above the plane of the cranium proper about half an inch and while somewhat accentuated by the depression of the cranial roof in front of the orbits, is not so conspicuous as in several other forms. This is due to the fact that the crest is but slightly depressed immediately in front of the nares.

OPENINGS OF THE SKULL

The position of the *nares* is that of the most highly specialized phytosaurs, high on the skull and not far from the eyes. The posterior border of the nares is about 105 mm. in front of the center of the orbit. The openings are 63 mm. long and about 21 mm. wide. They are separated by a moderately thin partition that does not reach the level of the outer borders. The plane of the combined openings is directed upward.

The *orbits* are slightly longer than wide, about 62 mm. in diameter.

The *antorbital fenestrae* are somewhat distorted. They appear to have been about 104 mm. long and perhaps 45 mm. wide. While they do not extend forward beyond the nares, as is the case in similar forms, this is due to the moderate length of the antorbital fenestrae and not to a unique position.

The sides of the *lateral temporal fenestrae* are restored in part. Because of this and some distortion it is not possible to give exact dimensions. It is thought, however, that the greatest diameter was not over 120 mm.

The *supratemporal fenestrae* show a development similar to that of *Mystriosuchus*.[1] The posterior border, i.e., the parieto-

[1] J. H. McGregor, "The Phytosauria, with Especial Reference to *Mystriosuchus* and *Rhutidodon*," *Mem. Am. Mus. Nat. Hist.*, Vol. IX (1906), Part II.

supramosal arcade is markedly depressed. The depression of this arcade has not advanced so far as in *Machaeroprosopus validus*.[1] The opening is very inconspicuous in a superior view because of the backward extension of the postorbital. The opening is directed out and back. It is slitlike, but its length cannot be determined because the outer posterior border is missing.

SEPARATE BONES OF THE DORSAL ASPECT

The *premaxillae* are gradually expanded laterally at the anterior ends for the accommodation of the large terminal teeth. The expanded portion is abruptly down-curved and extends about 30 mm. below the palate surface of the rostrum. At the margins of jaw, the premaxillae unite with the maxillae at about the twenty-fifth tooth. From this point the suture extends back and up in an irregular line. At the median line each premaxilla sends back a process to within 45 mm. of the nares. This process and a lateral posterior process extending back the same direction clasp the anterior process of the septomaxilla.

The *septomaxillae* are larger than in any other form that the writer has examined. They are united along the median line for a distance of 48 mm. and thence extend forward between the posterior process of the premaxillae a distance of 45 mm. The septomaxillae form a large area about the front and sides of the narial prominence, but their exact posterior extent cannot be determined. It is thought that they make up but a small part of the narial septum.

The *maxilla* has its greatest anteroposterior extent along the alveolar margin. In this respect it differs from the University of Wisconsin specimen referred to above.

The *nasals* form the posterior, median, and most of the lateral border of the nares. The lower anterior margin extends some distance beyond these openings, essentially as far as the septomaxillae. Posteriorly they extend about 35 mm. beyond the posterior border of the antorbital vacuity.

In the shape and extent of the *lachrymals* and *prefrontals* there is the normal phytosaur development.

The *parietals* differ from those of *Machaeroprosopus validus*[2] in

[1] Mehl, *op. cit.*, p. 8, Fig. 2.

[2] *Ibid.* p. 11.

that their combined width is equal to the interorbital width. Their length is 67 mm. and combined width the same.

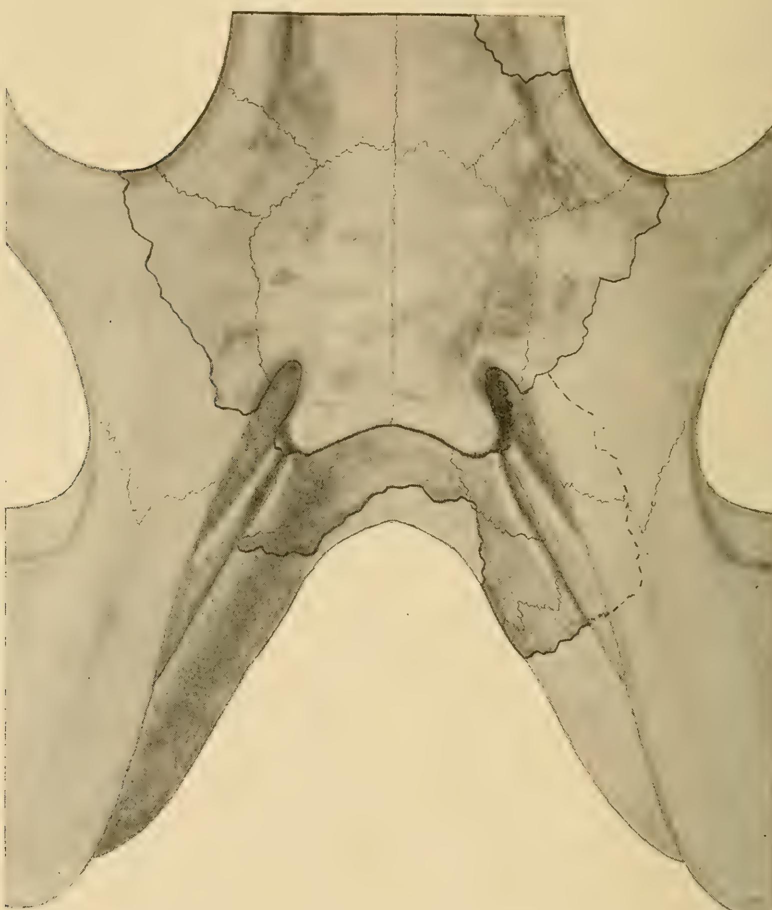

FIG. 2.—*Machaeroprosopus andersoni*, details of the posterior end of the skull as seen from above. Restored portions are indicated by lighter shading and less heavy outlines. Two-thirds natural size.

The *postfrontals* are small and make but a small part of the orbit boundary, as is usually the case.

The relation of the *postorbitals* is not clearly shown. The posterior extent of these bones cannot be determined, for that portion of the skull is restored.

The *jugals* form the lower posterior border of the antorbital vacuity, the lower anterior border of the lower temporal vacuity, and enter slightly in the boundary of the orbit. Along the lower border of the skull their posterior extent is such as to practically exclude the *quadratojugal* from that margin.

Little or nothing can be said of the squamosal development.

POSTERIOR VIEW OF THE SKULL

So much of the skull as seen from the posterior side is restored that little of value can be given in description. The skull has been telescoped downward, but it is evident that it was considerably wider than high. In so many details is the skull like the type of *Machaeroprosopus validus* that it is assumed the similarity extends to the posterior side. Some of the differences in the development of the region about the supratemporal open-

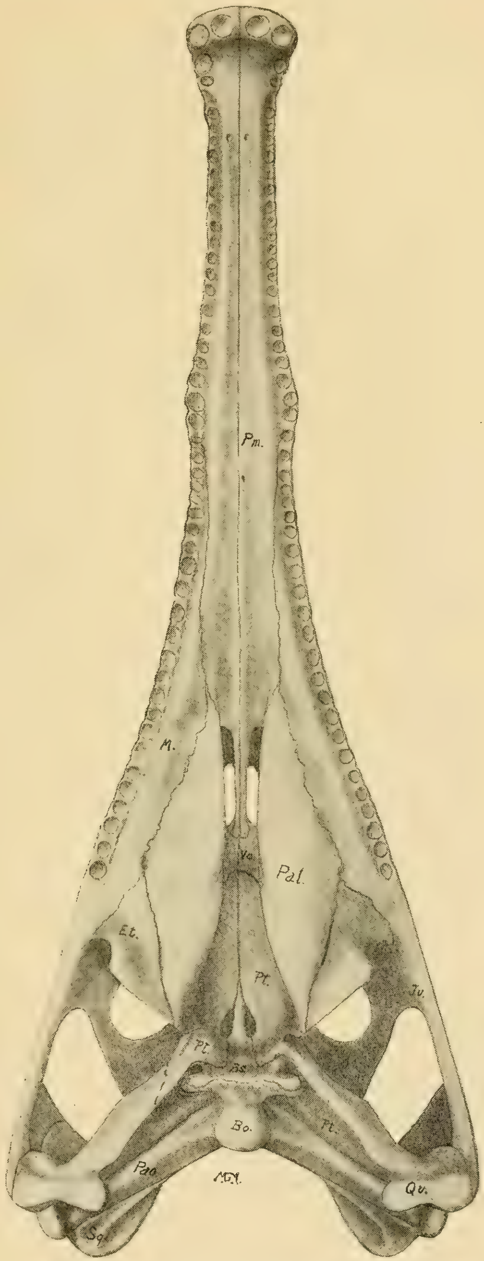

FIG. 3.—*Machaeroprosopus andersoni*, restored palate surface, slightly over one-sixth natural size.

ings are evident in a comparison of Figure 2 with that of *M. validus*.[1]

THE PALATE

The palate of this specimen (Fig. 3) seems very little distorted, but although the configuration of the bones is readily determined, some of the sutures are obscure. The bones are thin and overlapping, and the slightest abrasion tends to obliterate the unions.

The palate is marked by the characteristic phytosaurian ridges just within the alveolar border. These start indistinctly near the third tooth back of the down-turned terminus of the rostrum and increase in prominence to a point a little in advance of the internal nares. From here they flatten out posteriorly and lose their identity before the last tooth is reached. A slight median ridge, low and rounded, continues forward from the internal nares to about mid-length of the rostrum.

In the region of the twenty-third tooth, there is a conspicuous lateral expansion or swelling of the rostrum. The alveolar ridges broaden in this region to fill in the increased width.

Among the most striking features of the palate is the development of the narial arch. In *Angistorhinus*,[2] from the slight arching formed by the alveolar ridges far forward, the height increases gradually until it is broad and marked just in front of the nares. Here the height increases rapidly to about 42 mm. at the posterior end of the nares. At this point the arch has a width of 82 mm. In this genus there is not the slightest suggestion of the constriction of the arch at the lower palate plane, the suggestion of a primitive false palate.

In *Mystriosuchus*, as McGregor has shown,[3] the constriction of the narial arch at the lower palate plane is marked. To quote:

> This arched condition of the palate suggests two questions of great importance in their bearing upon the genetic relationships of the group, namely: (1) Do the Phytosauria exhibit the incipient formation of a secondary palate? and (2) if so, is this the first step in a phyletic series, culminating in the highly

[1] Mehl, *op. cit.*, p. 8, Fig. 2.

[2] M. G. Mehl, "The Phytosauria of the Trias," *Jour. Geol.*, Vol. XXIII (1915), No. 2, pp. 129–65.

[3] McGregor, *op. cit.*, pp. 42–43.

modified palate of the eusuchian crocodiles? As for the first of these questions I feel that there is no escape from an affirmative answer; an examination of the palate of either *Mystriosuchus* or *Phytosaurus* [*Lophoprosopus*] shows a pair of longitudinal palatine ridges . . . . which plainly represent the beginnings of a secondary palate. . . . .

The rounded inner border [of the portion of the palatine about the base of the narial vault] projects very slightly toward the middle line, so that the palatal aspect of the cranium exhibits two elongate ridges which approximate each other within 25 mm. at the level of the anterior border of the nares, diverging gradually behind this region. These palatine ridges partly obscure the outer part of the narial cavities and are continued anteriorly on the maxillaries, but fade out posteriorly without involving the pterygoid. . . . . It should be explained that these ridges do not present a sharp edge, but are broadly rounded. Nevertheless it is an approximation of the palatines, ventral to the internal nares and the pterygoids, and it seems to me that it must be interpreted as a *tendency* toward the formation of a secondary palate. . . . .

In the present form this tendency is so marked that there can be no doubt as to its meaning. The narial vault has its greatest width somewhat back of the nares. The cavity is still partly filled with matrix, but is at least 80–90 mm. wide and somewhat over 50 mm. high. So restricted is the arch at the lower palate plane by the median extension of the palatines, that the opening as seen in a palate view is little more than a slit, not over 24 mm. wide near the posterior border of the nares and gradually widening to the region of the interpterygoid vacuities. This constriction in the narial region is in the form of sharp-edged, thin, horizontal plates extending beneath the narial vault at the plane of the palate. The suggestion of an unfinished or rough edge bespeaks a cartilaginous or fleshy continuation. It is believed that the air passage was thus completely closed below for a considerable distance back of the nares.

The alveolar ridges cannot be considered as part of this "false palate," as is suggested by the foregoing quotation. In the present form they are quite distinct from the palatine extensions beneath the nasal vault. These alveolar ridges, always conspicuously developed in the phytosaurs, should probably be looked upon as buffers to prevent the breaking or interlocking of the teeth through the sharp snapping of the jaws in an unsuccessful attempt at seizing prey.

OPENINGS OF THE PALATE

The length of the *internal nares* is 71 mm., about 8 mm. greater than that of the external openings. The internal nares are about 20 mm. in advance of the externals at their posterior border.

The *postpalatine foraminae* are exceptionally small and inconspicuous. They are, in fact, little more than slight depressions or cracks along the palatine-ectopterygoid union. They are not over 30 mm. long and if actually perforating the palate are not more than 3 mm. wide.

The *interpterygoid openings* are exceptionally small. Their exact anteroposterior extent cannot be determined, but they could have been but little more than 25 mm. long.

THE BONES OF THE PALATE

Some of the details of the relations of the bones of the palate are not at all certain. In the palate restoration, the writer has attempted to show the relation as the weight of the evidence seems to indicate and not as indisputably determined.

The *premaxillae* apparently have a remarkable posterior extent on the palate surface. They seem to form the anterior border and the entire inner boundary of the internal nares and extend a short distance back of these openings along the median line. An unpublished drawing of this specimen by S. W. Williston doubtfully places the posterior end of the premaxillae about 40 mm. in front of the internal nares. The bone in this region is platey and brittle and has been somewhat abraded in preparation. The writer recognizes the possibility of the premaxilla-vomer suture in this region, but cannot verify this point.

The *maxillae* extend forward on the palate surface to the twenty-fourth tooth, numbering from the front. Their width on the palate is at no place much greater than that required for the alveolar ridges. The union with the jugal as seen in a palate is not determinable.

The *vomers* seem to be exceptionally small and confined to the posterior and possibly the posterolateral borders of the internal nares. This is a condition decidedly unlike that usually attributed to the phytosaurs and is merely suggested. What is assumed to be

the union of the premaxillae and the vomer at the inner posterior border of the nares may be a fracture. If so it is remarkable for its symmetry in relation to the median line of the skull. Of the posterior boundary there can be little doubt. It joins the pterygoid in a forward convex line about 32 mm. back of the internal nares.

The *palatines* apparently form a goodly portion of the lateral borders of the internal nares. Aside from this, however, they seem to be largely confined to the lower palate plane. It is thought that their union with the pterygoids and vomers is at or near the base of the narial vault, but of this one cannot be sure because of the matrix-filling part of the cavity. Posteriorly the palatines come to an acute angle, the point of which prevents the articulation of the pterygoids with the ectopterygoids on the palate surface.

The *ectopterygoids* are small, triangular bones. The posterior borders are down-curled so as to be conspicuous in a lateral view of the skull.

The *pterygoids* are exceptionally large, but are almost entirely confined to the sides and roof of the narial arch. Their extent along the pterygo-quadrate bar cannot be determined.

The *parasphenoid* has been destroyed, but it must have been very similar to that shown in the palate restoration. The union between the *basi-sphenoid* and the *pterygoids* and *basi-occipital* is as indicated in the restoration. The relation of the other bones of the posterior part of the skull as seen in the palate view cannot be determined. The relations shown are those determined from the University of Wisconsin specimen mentioned above.

THE TEETH

With the exception of a few roots and one partially erupted tooth in the middle of the series that shows the crown, all the teeth have been lost. The alveolar margin of the jaw is splendidly preserved for the most part and gives a good indication of the number of the teeth and of their variations in size.

The alveolae are all distinct and usually separated by a space of at least 3 to 5 mm. In each maxilla there are apparently twenty-four teeth and twenty-three in each maxilla, a total of ninety-four

in the upper dentition. In the downward portion proper of the premaxilla there are two alveolae of a size and shape to indicate long conical teeth of about 21 mm. diameter at the base. Immediately behind the down-turned portion is another large alveolus, about 15 mm. in diameter. This is followed closely by a fourth, considerably smaller, alveolus. Between the fourth and fifth alveolae is a conspicuous space. This is marked on one premaxilla by a depression as though for the reception of a tooth from the lower jaw. The following alveolae, with the exception of the last few on the premaxilla, increase gradually in size from about 6 mm. to 12 mm. There is a marked lateral expansion of the rostrum near the posterior end of the premaxillae for the accommodation of three or four exceptionally large teeth. The root of one of these is preserved and measures 13 mm. in diameter. The crown preserved in the maxilla series as mentioned above is laterally compressed with sharp, slightly serrate, anterior and posterior edges.

It would seem that the dentition was very much like that of *Machaeroprosopus validus*,[1] greatly enlarged seizing teeth in the front, grading through smaller, sharp, conical to laterally compressed slicing teeth behind. The space between the fourth and fifth alveolae indicates likewise a shorter jaw with large terminal teeth directed sidewise.

RELATIONSHIPS AND HABITS

Of the close affinity between the present specimen and that described as *Machaeroprosopus validus*[2] there can be no doubt; both skulls are crested forms of the "broken outline" type; both have the depressed posterior border of the supratemporal openings; and both have enlarged, conical terminal teeth with laterally compressed, sharp-edged, slicing teeth behind. The skulls differ in so many minor points, however, that they can scarcely be placed in the same species. The writer will designate the present form, therefore, as *Machaeroprosopus andersoni* in honor of Professor Anderson, who presented the material to the University of Chicago.

[1] Mehl, *Bull. Univ. of Oklahoma, op. cit.*, p. 20.

[2] *Ibid.*

The following table comparing the two forms will show the chief differences on which the new species is established.

Machaeroprosopus validus	*Machaeroprosopus andersoni*
Postero-median border of supra-temporal fenestrae completely depressed.	Postero-median border of supra-temporal fenestrae not completely depressed.
Anterior border of nares elevated above lateral borders.	Anterior border of nares not elevated.
Terminal expansion of rostrum abrupt.	Terminal expansion of rostrum gradual.
Nasals not extending to anterior border of nares.	Nasals extending some distance in front of anterior border of nares.
Greatest length of maxillae above alveolar margin.	Greatest length of maxillae at alveolar margin.
Approximately seventy-four teeth in upper dentition.	Approximately ninety-four teeth in upper dentition.
Six large teeth in terminal expansion of rostrum.	Four large teeth in terminal expansion of rostrum.
Alveolae crowded, occasionally confluent.	Alveolae not crowded.
No lateral expansion of rostrum at posterior end of premaxillae.	Lateral expansion of rostrum at posterior end of premaxillae.

The Phytosauria are a unified group in that they all tend to develop certain peculiarities that set them off from other groups in a striking manner. All developed the snoutlike elongation of the skull, an elongation that left the nares far from the tip. In some cases there seems to have been an actual retreat of the nares. There seems also to have been a tendency to elevate the nares above the plane of the cranium proper, a goal very conspicuously reached in several forms. All of the phytosaurs showed a more or less marked development of greatly enlarged terminal teeth and most of them developed at least a crude slicing dentition farther back in the jaws.

These modifications or tendencies are so distinctive that they have called forth considerable speculation as to the habits of the

phytosaurs. The seemingly common goal in the modifications of all the phytosaurs suggests similar habits. Of the probable habits of *Machaeroprosopus* the writer has stated in another place:[1]

All of the phytosaurs were supposedly more or less amphibious in habit. Still, the heavy dermal armor of several of the forms would indicate that a very considerable part of their time was spent on the land. The posterior position of the nares is usually not considered a distinct aquatic adaptation in the case of the phytosaurs. It is rather explained, along with the long snout and large terminal teeth, by attributing to the slender rostrum the function of a prod or rake with which the possessor searched out worms and other soft bodied invertebrates, etc., in the mud of shallow waters while the nares, by virture of their position, were above the surface of the water.

There is a marked tendency in most of the phytosaurs, a tendency in which *M. validus* surpasses all other known forms, for the nares to rise on a considerable prominence. This would seem to be a modification entirely uncalled for were the position of the nares due solely to the use of the rostrum as a prod. So situated are the nares in *M. validus* that it could submerge the body save for the narial hump and lie in wait admirably concealed from its enemies, or more likely, from its prey. Certainly the teeth of this form are more fitted for tearing large vertebrates than for small, mud-burrowing creatures. Then too, *Machaeroprosopus* could scarcely pick small objects from the ground because of the difference in length between the upper and lower jaws. When the jaws were closed the terminal teeth of the lower jaw were functionless and the upper terminal teeth were but little better. It was not until the jaws were wide open that the terminal teeth could be used effectively either as a rake or for seizing any sort of prey. With the jaws separated, however, the upper and lower terminal teeth were directly opposed and admirably fitted for seizing and tearing large animals. It seems likely that *M. validus* was wont to lie in wait concealed close up to the shore in shallow waters ready to seize its prey when the latter came down to drink. Once the prey was dragged into the water it was at the mercy of its captor, for the dentition of the latter probably matched that of any carnivorous land form of the time and the phytosaur had the distinct advantage of being entirely at ease in the water.

If these were the habits of the more highly specialized phytosaurs, and the assumption seems logical, the group was remarkably well adapted to the conditions of the times. The adaptation was, moreover, of a very peculiar nature. In most cases adaptations seem to do little more than tend to counteract adverse conditions. For instance, the development of speed in ambulatory forms of

[1] Mehl, *Bull. Univ. of Oklahoma*, *op. cit.*, pp. 23–24.

arid regions permits a wider range about the limiting water supply to compensate for the diminished food supply and the distance between water-holes.

In *Machaeroprosopus* the modifications not only met an emergency but actually turned it to advantage; the phytosaur waited for the rigorous conditions to bring his food within reach. If our interpretation of the conditions in the western interior of North America during Triassic times is correct the scarcity of food necessitated a wide range for many forms. This meant speedy forms ordinarily difficult of capture, but it also meant the periodic crowding of the limited water-holes; it compelled the food to walk to the captor.

It is not easy to see why a group so remarkably fitted to their environment as was the phytosaur group should not prosper better as a race. They were very short lived, confined to the latter part of the Trias, apparently. One can scarcely appeal to *over-specialization* unless this means "fitting in" rather than marked structural change. The phytosaurs were scarcely less generalized than the living crocodilians. Perhaps *perfection* alone is enough to condemn a race. A consideration of this possibility will form the basis for a future paper.

ADAPTING A SHORT-BELLOWS, ROLL-FILM KODAK FOR DETAIL WORK IN THE FIELD

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Most geologists, when in the field, have occasionally felt the need of a portable camera with which they might take large-size detail photographs. The ordinary equipment for such work, the long-draw, box camera, is far too heavy and bulky to be carried by the geologist as a part of his daily accoutrement. The roll-film kodak with the customary short bellows which is most convenient for his usual needs, fails when he wishes a picture larger than about one-tenth natural size, and the auxiliary portrait lens does not greatly increase the scope of his outfit. If he wishes a detail picture of a fossil in place, a curious marking or texture of a rock which cannot be conveniently sent to his headquarters, he must note the place and come again later with the more bulky equipment. He almost never does.

The device described below has been found by the writer to be a simple and convenient solution of the problem. An auxiliary portrait lens was first secured to fit the kodak he wished to use. This attachment consists of a simple plano-convex lens of about 52-inch focus. When placed close in front of the kodak lens this causes parallel beams of light to become slightly convergent when they strike the main lens system and thus shortens the focus of the combination (See Fig. 1, Scale II). With the principal focus now somewhat nearer the ground glass, the slight additional excess of bellows-length permits focusing on closer objects and hence larger pictures than with the kodak lens only.

Next, there were procured from an optician two more lenses of foci approximately 16 inches and 8 inches respectively. These were ground to the proper diameter to fit the cell belonging to the original auxiliary. The three lenses are readily interchangeable by unscrewing the ring which holds in place the lens used. By using

the two additional lenses, one at a time, the focus of the combination is further reduced, as shown in Scales III and IV of Figure 1. With the three used successively, the entire range of object-distance from infinity to less than eight inches can be accommodated, using only the two inches adjacent to the bellows-limit for adjustment.

After obtaining the lenses, the several combinations were calibrated for different distances by focusing on a ground glass placed in the image-plane and the readings made on a white celluloid metric

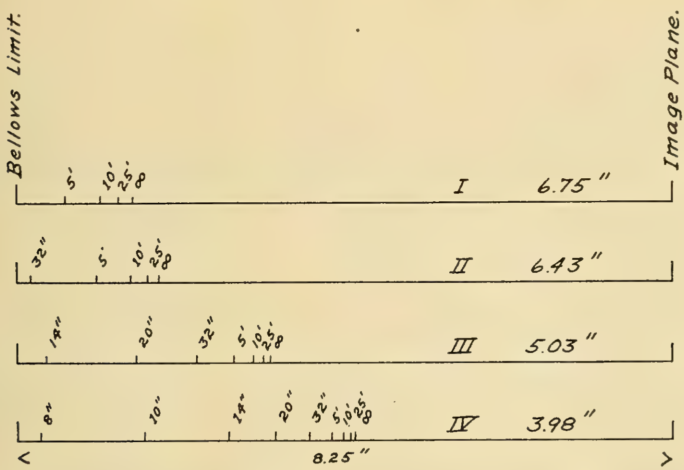

FIG. 1.—Diagram showing four focusing scales in relation to the image-plane and bellows-limit as follows: Scale I, with kodak lens of 6.75-inch focus; Scale II, using 52-inch focus auxiliary lens; Scale III, using 16-inch focus auxiliary lens; Scale IV, using 8-inch focus auxiliary lens. The figures at the right show the foci of the several combinations and the diagram shows clearly the increase in scope of the bellows as the auxiliaries of shorter focus are added.

scale which was attached to the bed, as shown in Figure 2. From these data were constructed the tables I and II which were photo-reduced and pasted in place on the bed of the kodak as shown. Here they are out of the way, but always convenient. Table I shows the setting on the metric scale for different object-distances, the three parts of the table referring, respectively, to the three auxiliary lenses, I, II, and III. Table II gives the object-distances for different ratios of object to image. For example, suppose one

wishes a picture which is one-half natural size. In Table II opposite the ratio 2 is given the object-distance 15 inches. Then in Table I, interpolating between 14 inches and 15 inches, we find that the focus should be at the scale-reading of 10.85 and that auxiliary lens II should be used. The kodak is then set with the lens 15 inches from the object to be photographed. Table II gives also at the bottom the foci of the three combinations, the focus of the kodak lens alone being about 6.75 inches.

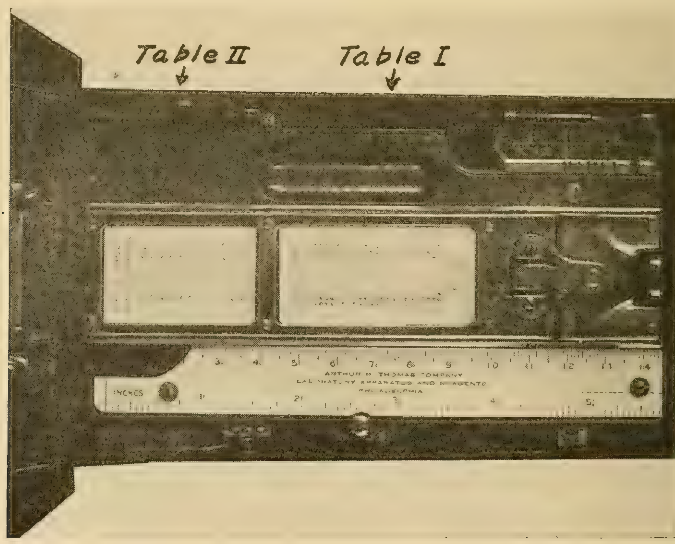

FIG. 2.—Photograph of bed of kodak showing attached metric scale and two tables as described in the text. (Somewhat reduced.)

The celluloid scale may, if desired, be so set as to read inches of focus from the ground glass directly; that shown was set arbitrarily and the readings indicate position only. With this device, sharp and undistorted photographs up to natural size may be taken by using a tripod or one of the numerous types of clamp support, and an aperture of F/32 or smaller. Since in pictures of this kind where the object is not plane, it is almost always necessary to reduce the aperture and give a time exposure in order to get depth of focus, there is no additional difficulty due to the auxiliary lens. Instantaneous pictures at full aperture may be made if need be, but the

distance must be estimated with considerable accuracy to secure good definition. Such rapid exposures are rarely necessary or even desirable in the case of geologic subjects.

Anyone desiring to use this device will find that auxiliary lenses of 52-inch, 16-inch, and 8-inch foci will be a suitable series for a 3A kodak having a lens of about 6.75-inch focus. For the use of others with different kodaks, the following formula is given:

$$\frac{1}{F_{0+1}}=\left(\frac{1}{F_0}+\frac{1}{F_1}\right)1.08$$

where F_0 = focus of kodak lens, F_1 = focus of auxiliary lens, and F_{0+1} = focus of the combination. This formula is only approximate but is sufficiently accurate to guide one in the selection of a series of auxiliary lenses. These lenses can be secured from any well-equipped optician who does his own grinding. They should then be calibrated by focusing on a ground glass in the image-plane and taking readings on the scale. Tables can then be constructed, as shown in Figure 2.

The extra lenses can be carried in any convenient pill-box. The cost for the three lenses and cell is less than five dollars and the outfit has been found by the writer during two seasons' field work to give highly satisfactory results.

SEGREGATION GRANITES

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The deposits of asbestus of the Eastern Townships in Canada are the most exploited of the world. In 1919 $18,000,000 worth or 3, 082,384 tons were mined. This means a great deal of development and has given J. W. Dresser, the geologist who has for years followed the region with the closest attention, a chance to make observations which are of general theoretical interest. Fifteen years ago[1] Dresser suggested that certain granites seemed to have been differentiated from the same magma from which were derived the serpentines in which the veins of asbestus chrysotile occur. This would tend to support Daly's idea[2] that granite is a product of differentiation from a basaltic substratum, *but not necessarily that it is "syntectic,"* that is, due to previous assimilation of something like a quartzite.

Some twenty years ago I had occasion to study with critical care what I then called "acid interstices" which practically always occurred near the middle of every diabase dike of over ten meters thickness or so.[3] I had over two hundred thin sections, and while Bayley and Irving and Wadsworth were inclined to believe the interstices filled with micropegmatite were secondary, I was inclined to agree with A. C. Lawson in believing them primary. By a careful study I convinced myself that such was the case. Later studies showed that the filling of similar interstices in effusive rocks was characteristically different, and I called the effusive texture doleritic. The conception I gathered was that these

[1] See *Bull. Geol. Soc. Am.*, Vol. XVII, p. 510; also *Canadian Survey Memoir*, Vol. XXII, and other papers by Dresser given in Ferrier's finding list.

[2] *Igneous Rocks and Their Origin*, p. 361.

[3] *Geological Survey of Michigan*, Vol. VI (1899), pp. 235–42, the work was largely done in 1890; see *Report of the State Board of Geological Survey of Michigan for the Years 1891 and 1892*, p. 177.

cavities were "filled with the residuum of the molten magma. Enough of the rock was formed to make it perfectly solid, for no further motion could take place without disturbing the micropegmatite borders of the felspar laths and fracturing the excessively delicate apatite needles. The remaining interstices seem, agreeing with the general law of increasing acidity in residual magmas, to have been filled with the final concentration of an acid aqueo-igneous magma which had been corroding the olivine and forming the less basic augite from it. In this magma were also concentrated the absorbed gases, aqueous and otherwise, which the dike margin originally contained and which, as the dike solidified at the margin, would probably be driven from it and concentrated at the center.

"The acid magma thus left seems to have proceeded to produce brown hornblende upon and out of the augite; brown mica upon and out of the iron oxides, as Smyth has suggested; and pegmatite growths on or out of the feldspar, while apatite needles formed across the cavities." The convincing arguments were that these interstices did not occur in marginal sections, and showed no signs of being more abundant in uralitic sections, but were best developed in otherwise fresh dikes, and were not present with superficial textures such as the amygdaloid textures.

The facts I have seen in the Medford diabase and elsewhere in the intervening thirty years have only strengthened the conviction that this interpretation is substantially correct, though it should be expressed not so much in terms of acid and basic, as in terms of those eutectic lines and troughs which the geophysical laboratory at Washington has worked out, the theoretical bearing of which has been developed by N. L. Bowen.[1]

The fluid magma from which the minerals of these interstices crystallized out would be closely held by capillarity if they were not large. But with increasing coarseness and size of interstices there would be more chance for it to drain out like honey from the honeycomb, or as Bowen and Harker have suggested, be squeezed

[1] "The Problem of the Anorthosites," *Jour. Geol.*, Vol. XXVIII (1919), pp. 393–434; *ibid.*, Vol. XXV, 3 (1917), pp. 210–44, "Crystallization—Differentiation in Igneous Magmas," and literature there cited; *Am. Jour. Sci.* (1915), p. 407; (1914), p. 207, etc.

out like fluid from a filter press. When this happens we have the aplitic red rock associated with the Duluth Gabbro described most fully and lately by F. F. Grout[1] or with that of Mount Bohemia, so fully described by F. E. Wright.[2] If one supposes this segregation conducted on a still larger scale or so that the crystallization shall be somewhat coarser and the grain coarser, the logical outcome would be a granite. This is just what Dresser finds that the advance of mining operations has conclusively proved[3] by showing that masses of granite have no separate connection with the earth's interior.

The largest mass of differentiated hornblende granite mentioned by Dresser is three-quarters of a mile long by one-quarter of a mile wide, with a coarser pegmatite border two or three feet wide and a porphyritic texture throughout. This granite "is an indication rather than a cause" of the presence of acid waters in the magmatic residue needed to produce serpentine and asbestos. It is interesting to note that Bowen starting with peridotite as a monomineralic differentiate suggested that the region "may" furnish a "complementary granitic differentiate." He is apparently right!

Now the laws of physics and chemistry are universal. If this has happened in the Lake Superior region and the Eastern Townships it must have happened in many other places. One is tempted to consider the Mull pitchstones[4] the "leidleites and inninmorites" which (*a*) apparently occur only as intrusions, (*b*) are high in primary water, (*c*) are glassy at the center and stony at the sides, i.e., coarser at the margins, as representing such a magma as that of the red rock of Wright, of Grout, etc., chilled more quickly and without loss of water, but yet like many aplites or the granite described by Dresser, consolidating more slowly at the margin. This I have shown is more likely to happen when the initial magma tem-

[1] "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI (1918), p. 618.

[2] *Report Michigan Geological Survey* (1908), p. 387.

[3] "Granitic Segregations in the Serpentine Series of Quebec," *Transactions of the Royal Society of Canada* (1920), pp. 7–13. Compare also N. L. Bowen, "Differentiation by Deformation," *Proc. Nat. Acad. Sci.* (1920), p. 160.

[4] E. M. Anderson, and E. G. Bailey, *Quart. Jour. Geol. Soc.*, Vol. LXXI (1916), pp. 205–16, London.

perature is low. In other words they are "secundine"[1] to the great series of basalts and gabbros.

The primary water-content (exceeding the average for rocks of similar composition) which Anderson and Bailey emphasize as characteristic is very suggestive. The analysis (1) of the glassy part of the leidleite may be very nearly that of the anchieutectic solution that once filled the acid interstices and that wandering off by itself would make red rocks and even hornblende granites. That though central it is glassy may be due partly to great viscosity and less power of crystallization, due to less lime, iron, and magnesia, and more silica, partly to a more rapid passage through the crystallization range of temperature, even though later.

If we study these analyses (see following table), 1 and 2 given by Anderson and Radley, and compare with 3 and 4, Bowen's analyses of Canada diabase and dike granite and with the average igneous rock as given by Clarke and Daly we find, (1) that they are not very far from the average igneous rock, (2) that they are not very far from the eutectic trough or line to which I called attention in 1904,[2] (3) that they are not very far from the analyses of the red rocks given by Grout and Wright, etc., (4) that the

[1] I have found the following classification of dikes with the appropriate adjectives to have some value:

1. *Invasive.*—Forced more or less slowly into cavities formed by the extra hydrostatic pressure of the invading magma; contacts irregular and often close-welded.

2. *Suctive.*—Forced quickly into a crack otherwise opened, by fault or earthquake relieving strain, aided by gravitative suction, owing to the condensation by cooling of the gases from the magma; contacts generally fairly straight and not close-welded.

Nearly parallel is a classification according to the hot or cold condition of the country rock as follows:

1. *Secundine* (Latin *secundine*=afterbirth).—Injected into a hot country rock; contact generally irregular, close-welded, the grain generally equal throughout, either finer or coarser at or near the margin.

A characteristic mode of occurrence of lamprophyres, aplites and pegmatites.

2. *Subsequent.*—Injected into a cold country rock, with fine-grained selvages (the zones of increasing grain amounting to from one-quarter to one-tenth of the breadth of the dike) with straight and not close-welded contacts.

A characteristic occurrence of dikes not closely connected with larger masses or volcanic centers, and in composition close to Bunsen's normal basaltic magma or more basic.

The anchieutectic rocks which we are discussing are generally invasive secundine, but in case of shrinkage cracks, due to loss of heat or contact metamorphism, may be suctive and secundine too.

[2] *Jour. Geol.*, (1904), p. 91. See also *Wet and Dry Differentiation*, "Tufts College Studies," Vol. III, Pt. I.

stony margin (An. 2) in its less silica, more lime and magnesia is not so far on the toboggan slide toward the goal of "wet differentiation"—the magma from whence crystallizes pegmatite veins, and not so near to a granite (An. 4) as the glassy center (An. 1). We seem thus to have caught two stages in a differentiation which carried on on a large scale would lead to the hornblende granites described by Dresser.

As to the syntexis upon which Daly lays stress, there is no doubt that the inclusion and absorption of fragments of sandstone, *especially if they contained water in the interstices*, should promote the formation of micropegmatite, and zones of micropegmatite around such fragments in process of absorption are found in the Medford diabase, as Jaggar and others have seen. Possibly the water is quite as important as the silica. Very likely much of the red rock of Pigeon Point is of this nature. But the association of micropegmatite with diabases is too widespread for me to agree with Daly[1] that most granites are differentiates of syntectics. It is well worth considering how many are, like that described by Dresser, direct differentiates with the help of juvenile juices or mineralizers.

Oxides	1 Glassy Central Leidleite	2 Stony Marginal Leidleite	3 Diabase Cobalt	4 Granite from Cobalt
SiO_2	61.69	59.21	50.12	72.33
TiO_2	1.00	1.06	.55	.74
Al_2O_3	14.43	14.06	15.70	12.99
Fe_2O_3	1.23	2.66	1.42	none
FeO	5.86	4.87	6.89	2.50
MnO	0.30	0.24	.....	.....
CaO	4.97	5.95	11.30	1.73
MgO	2.81	3.71	9.50	0.97
Na_2O	3.20	2.06	2.91	7.60
K_2O	1.72	2.83	1.07	.....
BaO	0.04	0.03	none	.....
H_2O at 105° C	0.25	2.05	1.03	1.09
H_2O above 105° C	2.36	1.54	0.21	.....
Total	100.12*	100.47 †	100.84 ‡	100.95 §

* Including 0.02 Cl. 0.24 P_2O_5 † Including 0.2 P_2O_5.

‡ Bowen in *Can. Mining Inst.*, Vol. XII (1909), p. 523, diabase, including 14 S.

§ *Ibid.*, granite cutting diabase, including 1.00 CO_2.

[1] *Op. cit.*, p. 312, etc.

ON THE REPRESENTATION OF IGNEOUS ROCKS IN TRIANGULAR DIAGRAMS

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It has been customary to represent three components in a triangular diagram by a dot, or four components by a triangle within the triangle. The writer, by means of only a dot and a line, plots without the use of a slide rule or any calculation whatsoever, the actual percentages of quartz, orthoclase, plagioclase, and dark minerals as well as the relative percentages of quartz, orthoclase, and plagioclase among the light constituents.

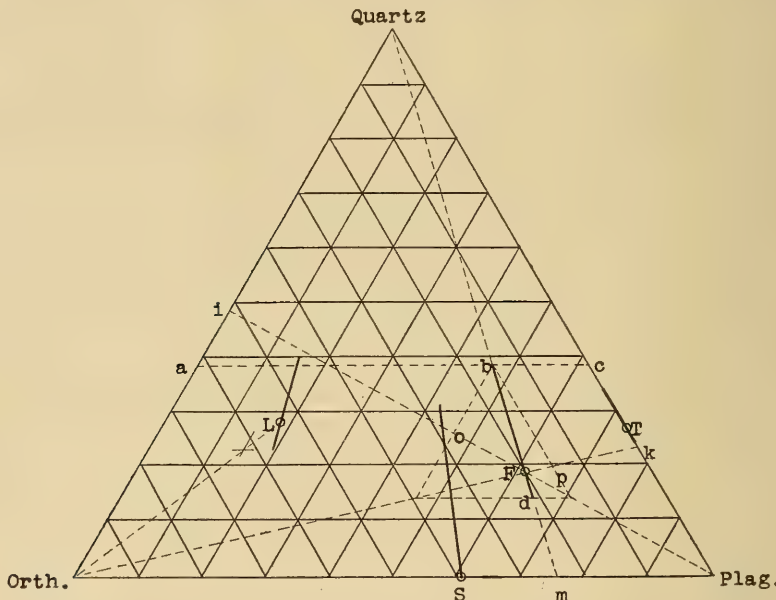
Let it be required to plot a rock with the following mode:[1]

Quartz	14=	18.7
Orthoclase	15=	20.0
Plagioclase	46=	61.3
	75	100.0
Dark minerals	25	
	100	

The usual method is to reduce to 100, by means of a slide rule, the sum of the percentages of the minerals represented in the three corners of the diagram, and plot the point so obtained. The writer's method is shown in the figure. Draw three lines, parallel to the sides of the triangle, through the points representing the amounts of the corner minerals in the rock, in this case a horizontal line through 14 for quartz, a line sloping northeast and southwest through 46 for plagioclase, and a line sloping northwest southeast through 15 for orthoclase. Lay the side of a straight-edge on the apices of the two triangles and draw a short line (*bd*) through the small triangle from its apex to its base. Connect either of the

[1] The same method may be used in other ways to show the relative percentages of three components whose sum is not a hundred.

lower corners of the large triangle with the similar corner of the small one, and indicate its intersection with the line first drawn by a dot, *F*. The line *bd* and the spot *F* represent the rock. The point *F* is the same as that which would have been obtained by the slide rule, and gives the relative proportions of the light constituents (quartz [*mF*], orthoclase [*kF*], and plagioclase [*iF*]), in



the rock by its distances from the sides of the triangle opposite these names at the corners. The actual percentages of the minerals in the rock are also represented: *bc* or *pk* for orthoclase, *ab* or *io* for plagioclase, *bd* for the dark constituents, *dm* for quartz.

In a similar manner the composition of the rock at *L* may be read directly from the diagram, giving the values:

Quartz	23=	27.7
Orthoclase	45=	54.2
Plagioclase	15=	18.1
	83	100.0
Dark minerals	17	
	100	

The rock at S is seen to consist of orthoclase 27 per cent, plagioclase 42 per cent, quartz 0 per cent, and dark minerals 31 per cent. The relative ratios of the light constituents are: orthoclase 39.1 per cent, plagioclase 60.9 per cent, and quartz 0 per cent. The rock at T consists of orthoclase 0 per cent, plagioclase 66 per cent, quartz 24 per cent, dark constituents 10 per cent. Relative ratios of the light minerals, plagioclase 73.5 per cent, quartz 26.5 per cent, and orthoclase 0 per cent.

The actual plotting takes much less time than the telling. In fact the small triangle is never plotted. The upper end (b) of the line is located at the dividing point between orthoclase (bc) and plagioclase (ab) on the horizontal line whose length (ac) is equal to the sum of the feldspars, and through this point the inclined line is drawn to the percentage position of quartz (d). One of the lower corners of the small triangle is located, without drawing it, and the intersection of the inclined line with the ferromagnesian mineral line used to determine the locus of the rock.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Adams, Sidney F. "A Microscopic Study of Vein Quartz," *Econ. Geol.*, XV (1920), 623–64. 48 figs. on 8 pls.

This study of the microscopic characteristics of vein quartz is confined to quartz of hydrothermal origin; magmatic, metamorphic, and replacement quartz are not included. A well illustrated and instructive paper.

Allen, E. T., and Lombard, Robert H. "A Method for the Determination of Dissociation Pressures of Sulphides, and Its Application to Covellite and Pyrite," *Amer. Jour. Sci.*, XLIII (1917), 175–95.

A secondary enrichment investigation of the Geophysical Laboratory, in which methods and apparatus are described.

Andersen, Olaf. "On Aventurine Feldspar," *Amer. Jour. Sci.*, XL (1915), 351–99. Figs. 13, pls. 3.

The schiller in certain feldspars was determined as being due to oriented, lamellar inclusions of hematite of various shapes and sizes. They originated through the unmixing of an originally homogeneous feldspar which contained iron oxides in solid solution. The lamellae were found always to be oriented after simple crystal forms.

Backlund, Helge. "Petrogenetische Studien an Taimyrgesteinen," *Geol. Fören. i Stockh. Förhandl.*, XL (1918), 101–203. Figs. 11, map 1.

This is a petrological study based upon about 500 specimens collected by the unfortunate Baron v. Toll in his expedition to Taimyr Peninsula, in northern Asia. The region is made up of gneisses, mica, and other schists, contact hornfeld-like rocks, and three types of granite. Many of the rocks were analyzed, and they are computed into norms and into the Osann system, while under granite the percentage modes

also are given. Besides detailed descriptions of the various rocks, there is a good discussion of movement in solidified rock, illustrated by numerous diagrams.

BARRELL, JOSEPH. "Relations of Subjacent Igneous Invasion to Regional Metamorphism," *Amer. Jour. Sci.*, I (1921), 1–19, 174–86, 255–67.

This paper, written by the late Professor Barrell in 1913 or 1914, has been edited and seen through the press by Frank F. Grout, and no better abstract of it can be given than Mr. Grout's own summary.

Evidence is presented that batholithic invasions widen downward and may occur close below many rocks where they have not been suspected. Batholiths like those in the American Cordillera seem to come to place without crustal compression, but those of the Archean shield and those of the later Appalachian invasions are accompanied by compression. A detailed study of three or four regions shows the metamorphism to be related to the igneous invasion more than to the depth and pressure. One of the regions of deepest burial and close folding in Pennsylvania shows slight metamorphism.

The action of magmas, both by heating and metasomatism, is reviewed. The solutions are not meteoric in origin. The results in minerals depend on equilibria—largely on the presence of H_2O and CO_2. The depth of anamorphism may be small, due (1) to weakness of some rocks, (2) to invasion of batholiths. An argument for shallow depth is based on the completeness of Archean metamorphism and the salt of the ocean as a measure of erosian.

The features of metamorphic rocks are reviewed and interpreted as due to one or another factor. Major factors are batholithic invasion and compression. Movements of solutions, selective crystallization, lit-par-lit injection gneisses, and the alternation of injection and mashing, each leaves its marks.

BARTRUM, J. A. "The Conglomerate at Albany, Lucas Creek, Waitemata Harbour," *Trans. New Zealand Institute*, LII (1920), 422–30. Pls. 2.

The conglomerates of the Albany Riverhead district (probably of Upper Miocene age) contain pebbles of greywacke, argillite, granodiorite, quartz-diorite, diorite-gneiss, diorite, anorthosite, dolerite, andesite, trachyte, and rhyolite. In this paper the igneous rocks are briefly described and four photomicrographs are given. It is suggested that the gneissic rocks in conglomerates, here and elsewhere in the North Island, perhaps furnish evidence of a terrain injected by batholitic intrusions, subjected to compressional stresses, and eroded before the deposition of the main mid-Mesozoic sedimentaries.

BARTRUM, J. A. "Additional Facts Concerning the Distribution of Igneous Rocks in New Zealand," *Trans. New Zealand Institute*, XLIX (1916), 418–24. Figs. 3.

Brief descriptions are given of hypersthene-basalt, troctolite, granodiorite with epidote (which the writer, not the reviewer, thinks primary), basalt with biotite (character of the feldspar of the rock not given), hornblende-basalt, andesite, diorite, and trachyte. Most of the descriptions are too brief and incomplete to permit passing judgment on the names.

BARTRUM J. A., "Additional Facts Concerning the Distribution of Igneous Rocks in New Zealand: No. 2," *Trans. New Zealand Institute*, LII (1920), 416–22. Figs. 5.

Here are brief descriptions of norite, dolerite, basalt, and hypersthene-andesite, and one more extended of quartz-norite. The dolerite is apparently the diabase of United States usage. The quartz-norite is described as "a moderately typical norite but for two considerations: first the plagioclase . . . . is somewhat acid, being in the main andesine-labradorite; secondly, there is . . . . a little interstitial quartz." A third objection which might have been given is the fact that besides hypersthene there is abundant augite, biotite, some hornblende, and "probably a third pyroxene." With a feldspar more acid than $Ab_{50}An_{50}$ why not call the rock quartz-hypersthene-diorite? The "third pyroxene" is described in considerable detail. All but one of its properties, including orientation, agree with hypersthene, the exception being the "extinction angle which was found to be from very small to 42°." *May* this mineral not be hypersthene? The reviewer has found that this mineral, in many cases, gives apparently inclined extinction in sections which are cut at right angles to the principal sections and yet show only one set of prismatic cleavage lines brought out by the grinding. Measuring then from the cleavage lines, the extinction is inclined, but it will usually be seen, if the stage is turned an equal number of degrees beyond the point of extinction, that there are here traces of the other cleavage. Random sections cutting all three axes in orthorhombic crystals do, of course, show inclined extinctions when measured from cleavage lines. Zoisite is mentioned as a mineral originally identified as apatite, and surprise is expressed that apatite does not occur although the analysis gives considerable P_2O_5. The sketch given of this

mineral may well represent a corroded apatite of a form not uncommon, and its occurrence surrounded by magnetite is indicative of the same mineral. Unless the fragments were large enough to permit of absolute determination as zoisite, the reviewer is inclined to think the original identification correct.

BECKE, F. *Ueber den Monzonit.* Festschrift C. Doelter. Dresden and Leipzig, 1920, 1–14. Fig. 1.

Monzonite, originally a collective name for all the different rocks found on Predazzo and Monzoni, has been variously used. Becke gives the following definition: Monzonite is a plutonic rock of granular texture. Its essential constituents, in the order of their crystallization, are magnetite, augite, hornblende, biotite, plagioclase (average composition andesine), and perthitic orthoclase. Small amounts of quartz or aegirite-augite or nephelite may occur. Accessory minerals are apatite and titanite. The dark and light constitutents, also the orthoclase and plagioclase, are of approximately equal amounts. Chemically the An: Ab: Or ratios are about 20:45:35; and the Ca:Mg:Fe=30:30:40. SiO_2 fluctuates around the point of saturation, so that quartz or a feldspathoid may occur in small amounts. Becke objects to the use of the term monzonite as applied to rocks of the "Pacific type." The silica content must be below 63–64 per cent. The term thus used is dependent upon the chemical composition. Used in the foregoing sense, many rocks described as quartz-monzonites are not such at all.

BENSON, W. N. "Report on the Petrology of the Dolerites Collected by the British Antarctic Expedition, 1907–1909," *Geology*, Vol. II, of Shackleton's Report. London, n.d., 153–60. Figs. 6.

Dolerites, in this report, are rocks composed essentially of basic plagioclase and pyroxene, with varying amounts of quartz. Following British usage they are called dolerites (diabases, United States). Since the name was originally given by Hauy to coarse-grained basalts, the use of the expression aphanitic dolerite seems anomalous. Several analyses, recast in the C.I.P.W. system, are given, and the rocks and component minerals are described in detail.

Benson, W. N. "The Origin of Serpentine, a Historical and Comparative Study," *Amer. Jour. Sci.*, XLVI (1918), 693–731.

The author agrees with the general opinion that chrysotile- or antigorite-serpentine of large ultrabasic masses is derived from the alteration of originally intrusive peridotite; the hydration, in some cases at least, having been brought about by the agency of waters emanating from the same magma as that which produced the peridotite. Whether a peridotite which escaped hydration during the igneous epoch can subsequently be changed to serpentine by the action of deep circulating epigene waters is regarded as less clear though thought not improbable. The reviewer is glad to see followed here his own mode of indicating by asterisks, in the bibliography, works not seen by the writer.

Benson, W. N. "The Geology and Petrology of the Great Serpentine Belt of New South Wales," Parts VI (Appendix) and VII. *Proc. Linnean Soc. New South Wales*, XLII (1918), 693–700, XLIII (1918), 320–94. Map 1, pls. 10, figs. 5.

The preceding papers of this series were reviewed in *Jour. Geol.*, XXV (1917), 493–95. In the present papers the rocks of the Attunga and Loomberah districts, and of a portion of the Goonoo Goonoo Estate are described. Two analyses of dolerites are given and keratophyres, dolerites, albite-dolerites, and granophyres are described rather completely, although much-to-be-desired model percentages are not given.

Berek, M. and Jentzsch, F. "Ein kleiner lichtstarker Monochromator, besonders für mikroskopische Beobachtungen," *Zeitschr. f. Instrumentenkunde*, 1914, 47–51. Figs. 2.

Describes a small monochromator for the production of monochromatic light. The instrument is only half as large as a petrographic microscope, and is so arranged that the whole spectrum may be made to pass through the opening without adjusting the light source or the microscope. The visible portion of the spectrum is normally 12 mm. but the emergence slit may be adjusted to any width. The emerging ray may be made parallel, convergent, or divergent by means of a lens in a sliding tube.

REVIEWS

Life of James Hall, Geologist and Paleontologist, 1811–1898. By J. M. CLARKE. Published by S. C. Bishop, Albany, N.Y., 1921. 8vo, pp. 565, pls. 14. Price $3.70 postpaid.

In this handsome volume of 565 pages, the deft pen of Dr. Clarke has set forth the life and times of James Hall in a most illuminating and fascinating way. While the story holds with tenacity and strict fidelity to the realities of Hall's remarkable career, the handling of its varied incidents is none the less most skilful, and the book is worthy of being read as a work of art. All the way through it bears evidence of unsparing labor in searching out from voluminous correspondence and tedious official records the essential details that give precision and life to the sketch. It is written from a deeply sympathetic and appreciative point of view, but the angularities and irascibilities of a strong and intensely earnest man are given their due place in the portraiture. These are touched with wonderful skill, so that they seem merely incidental shadows artistically designed to set off the high lights of the picture.

The book, however, is far more than a biographical sketch; it carries the reader into the very heart of investigative work as it was in those early times, while incidentally not a little light is thrown on the status of the allied sciences of the day. It gives most interesting glimpses of the leading scientific men of the time, including many of the foremost men in other than the geological sciences. Dr. Hall had a wide acquaintance with these, and the abundant extracts from his intimate correspondence with them shed suggestive side lights on the personal aspects of pioneer investigation and the troubles, political and otherwise, which attended it. We doubt if there is any other text that carries the reader so close home to the inner history of our own and allied sciences in this country during the early and middle stages of the last century. No student of geological and paleontological progress should miss the opportunity to read this thesaurus of information on a most vital stage of early American science.

T. C. C.

The Geology of Northeastern Rajputana and Adjacent Districts. By A. M. Heron, B.Sc., F.G.S., Assoc. Inst. C.E., Assistant Superintendent Geological Survey of India. Calcutta: Memoirs of the Geological Survey of India, Vol. XLV, Part I, 1917. Pp. 128, pls. 26.

This report gives the results of a general geological survey of the region started in 1908, made with special reference to stratigraphy. The formations present include only the pre-Cambrian overlain by unconsolidated post-Tertiary beds. The chief physiographic feature is that of an ancient, folded, mountain complex, in the last stages of denudation, surrounded by gently sloping plains. There is a general discussion of local correlations and nomenclature.

There is no mineral wealth of any great importance. Quartzite is quarried rather extensively, but chiefly for local use. The report is accompanied by a geologic map and a number of structure sections.

A. C. McF.

The Phosphate Deposits of South Australia. By R. Lockhart Jack, B.E., F.G.S. Adelaide: Geological Survey of South Australia, Bulletin No. 7, 1919. Pp. 135.

The author considers briefly the mode of occurrence, sources, method of working, and the preparation of the rock phosphate. Both guana deposits and rock phosphate are worked. The latter is associated with sedimentary rocks of Cambrian or even possibly pre-Cambrian age which are usually highly metamorphosed. It is almost invariably found in close association with the limestones and marbles or the adjoining argillaceous rocks. Whether the phosphate is primary or secondary is not known. Brecciation of the associated rock is conspicuous even at considerable depth.

A. C. McF.

Systematic Report on the Cambrian and Ordovician of Maryland. By R. S. Bassler. Maryland Geological Survey, 1919.

In a review of this report in the last issue of this *Journal*, it was stated that the proposed Ozarkian and Canadian systems "are not recognized" instead of "are recognized." It is the desire of the reviewer to call attention to this correction. The two systems are not only recognized but are discussed in some detail, the Conococheague limestone being referred probably to the former, and the Beekmantown limestone to the latter.

A. C. McF.


A
PHYSIOGRAPHIC DIAGRAM
OF THE
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Among articles to appear in early numbers of the *Journal of Geology* are the following:

A Criticism of the "Faunal Relationships of the Meganos Group," by Bruce L. Clark. By ROY E. DICKERSON.

Post-Glacial Lakes in the Mackenzie River Basin, Northwest Territories, Canada. By A. E. CAMERON.

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The Age of the Domes and Anticlines in the Lost Soldier-Ferris District, Wyoming. By A. E. FATH.

A Scale of Grade and Class Terms for Clastic Sediments. By CHESTER K. WENTWORTH.

ERRATA

Journal of Geology, Volume XXX, on page 164, line 2 from the bottom, and page 165, line 2 from the top, read Radley, instead of "Bailey."

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THE

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THE REACTION PRINCIPLE IN PETROGENESIS

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INTRODUCTION

It is now many years since petrologists first began to think of the crystallization of a molten magma in terms of the physico-chemical principles governing the behavior of solutions. In the study of ordinary solutions a condition frequently found was that known as the eutectic relation. In the simple case of two components, each lowered the melting-point of the other to the temperature of the eutectic point, at which temperature both solids separated side by side from a solution of fixed composition, the eutectic mixture. This case and the analogous condition in systems of more components are now so familiar to petrologists that they need not here be enlarged upon. The concept of the eutectic was early seized upon by petrologists and has been one of great utility in petrogenic theory. It accounted for the low melting temperatures of mixtures of minerals that are individually highly refractory. It threw light on some of the factors governing the separation of minerals from their mutual solution. But most of all, it stimulated the tendency to think of magmas in the light of the laws of solutions, or, better, of phase equilibrium, and encouraged experimental research whose expected result was the location of the composition of the eutectics for chosen mineral

mixtures. In investigation of this kind, both on its theoretical and experimental sides, Vogt took a leading part and the importance of his pioneer work cannot be overestimated.

As might have been anticipated, it was soon found that the eutectic relation did not always obtain, for, after all, it is but one of many possible relations between two or more components in any system. Very early it was realized that the existence of solid solution between two components might eliminate the eutectic relation between them. Later, as more accurate methods of experimentation were introduced, examples of incongruent melting were found, which again lead to the elimination of the eutectic. Indeed, it seems that relations between the components such that the eutectic disappears are so common in mineral systems that it may be doubted whether considerations based upon the doctrine of eutexia can longer be regarded as of any great service to petrogenic theory, in spite of their great suggestive utility in the past.

It should be realized that these non-eutectic relations should not be termed anomalies nor even apparent anomalies. They are just as definitely the result of the laws of solution as are eutectics.

This paper has been written with the object of readjusting the emphasis in our conception of mineral relations. It will be pointed out that another relation between the phases, here called the reaction relation, is very common in silicates, and is at the same time a very much broader concept, with which to approach the study of petrogenesis, than the simple doctrine of eutexia, so that it might well be set up as a principle to serve as a guide and stimulus to the search for facts.

OF CONTINUOUS REACTION SERIES

The reaction relation in a common form is illustrated by the case of the plagioclase feldspars. The equilibrium diagram of the plagioclases (Fig. 1) is of a simple and familiar type.[1] Those features of it that require emphasis in the present connection may be brought out very briefly. The crystallization of any random liquid, say Ab_1An_1, takes place in the following manner. At 1450° crystals of the composition Ab_1An_4 begin to separate. As the

[1] N. L. Bowen, *American Journal of Science*, Vol. XXXV (1913), p. 583.

temperature falls the amount of crystalline matter increases and at the same time changes in composition along the solidus curve. Thus at 1370° the crystals have the composition Ab_1An_2. In other words, the first-formed crystals have suffered a change of composition; indeed, they are continually modified in composition by *reaction* with the liquid. Crystals and liquid mutually influence each other throughout the course of crystallization.

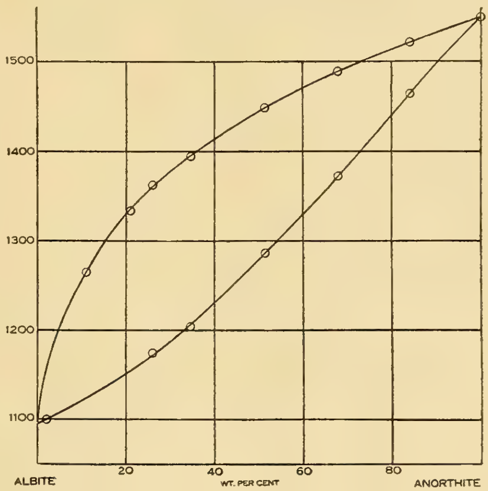


FIG. 1.—Equilibrium diagram of the plagioclase feldspars.

All of this is now an old story and is repeated here merely to emphasize the marked difference in crystallization between a mixture in such a system and one in a eutectic system. In this latter, a crystal once separated is no longer concerned in the equilibrium, which makes it in every respect a special case whose occurrence might be expected to be comparatively infrequent, particularly in more complicated solutions (magmas).

On account of the continual reaction relation between crystals and liquid in a solid solution series such as the plagioclases, it is proposed, for the purposes of the present paper, to call such solid solutions a *continuous reaction series*. The term will apply to any solid solution series, whether to a complete series such as the plagioclases or to each separate series in the case of incomplete solid solution.

The essential feature of a reaction series, the reaction relation of crystals and liquid, is retained when the series becomes a part of a more complex system. This is true even when the end members of the series bear a eutectic relation to the newly added component, as is well shown when diopside is added to plagioclase. The

equilibrium diagram of this system is given in Figure 2. Again it is a familiar diagram that has been fully discussed in other places,[1] but certain features of it require emphasis in the present connection.

A mixture of composition F (diopside 50 per cent, Ab_1An_1 50 per cent) begins to crystallize at 1275° with separation of diopside. As the temperature falls the crystals merely increase in amount.

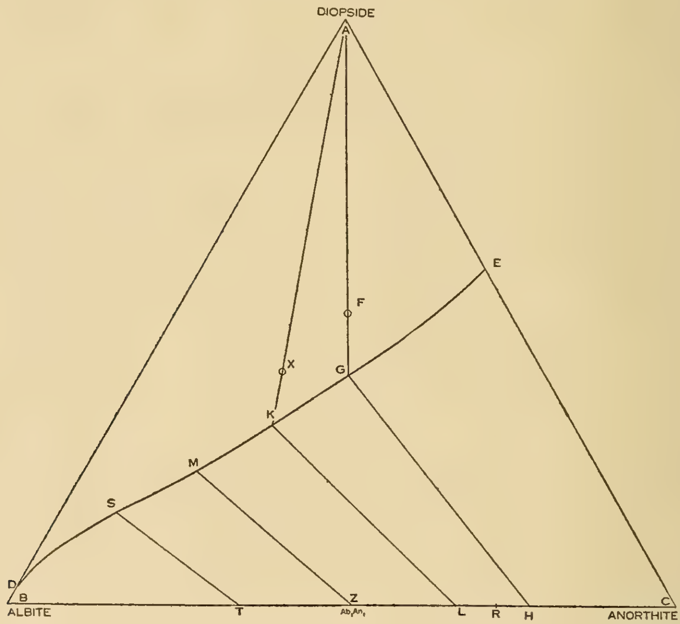


FIG. 2.—Crystallization diagram in the system, diopside-anorthite-albite

At 1235°, when the liquid has the composition G, plagioclase of composition Ab_1An_4 begins to separate and thereafter the change of composition of the liquid is represented by the boundary curve *ED*. And as crystallization proceeds along the boundary, the same reaction relation exists between the plagioclase crystals and the liquid as in the binary system. Vogt would call the curve *ED* a eutectic boundary curve or eutectic line and, to be sure, it has some properties in common with such a line.[2] It marks the composition of

[1] N. L. Bowen, *op. cit.*, Vol. XL (1915), p. 175.

[2] J. H. L. Vogt, *Journal of Geology*, Vol. XXIX (1921), p. 429.

the liquids that are in equilibrium with two solid phases. Moreover, it lies along a valley in the fusion surface and when the object is to emphasize these features no serious objection can be raised to the term used by Vogt. On the other hand, such a usage would tend toward a non-recognition of the importance of the reaction relation between plagioclase crystals and the liquids lying along the boundary curve and, in the writer's opinion, petrology will better be served by emphasizing this relation—calling the curve, say, a reaction curve. But quite apart from the question of nomenclature, the distinction is really one of fundamental importance in petrogenesis. In the case of a true eutectic line in a ternary system, the two kinds of crystals separating bear what may be called a mere subtraction relation to the liquid and once subtracted they are no longer concerned in the equilibrium. Moreover, the true eutectic line ends in a ternary eutectic point which represents the composition that all liquids of the system must finally attain and beyond which they never pass. No such rigidity obtains in a system where the reaction relation enters. The composition of the final liquid depends upon the freedom with which reaction between crystals and liquid may take place. If the reaction is complete in the example taken, the crystals are continually made over and the last of the liquid is used up by the reaction at 1200°, when the composition of the liquid is M and all the crystals have the composition Z. But if for any reason early crystals do not participate to the full in the reaction—and this may occur when zoning of crystals or sinking of crystals supervenes—the composition of the liquid may then pass beyond M and the final liquid have a composition represented by some point between M and D, with corresponding effect on the composition of the final crystals.[1]

This flexibility in the behavior of the liquid is entirely the result of the reaction relation between liquid and crystals. The course of crystallization is rendered responsive to the conditions under which crystallization takes place, for removal of crystals by zoning, sinking, or otherwise is entirely dependent on these conditions. No such response is possible in a eutectic system, for,

[1] A similar effect may of course be brought about in the binary system of the plagioclases, but it was considered unnecessary to discuss it for each case separately.

whatever the conditions, the eutectic is the goal of all liquids; all attain it; none pass it; it is a "fen of stagnant waters."

OF THE REACTION PAIR AND DISCONTINUOUS REACTION SERIES

The kind of reaction relation introduced by the existence of a solid solution series is not the only kind that is of importance in crystallizing magmas. Another type of crystallization phenomenon, ordinarily to be thought of as quite distinct from solid solution, has, nevertheless, consequences of a similar nature. This type is illustrated in several systems that have been investigated experimentally, but for our present purpose we shall discuss only cases showing phases closely related to rock minerals.

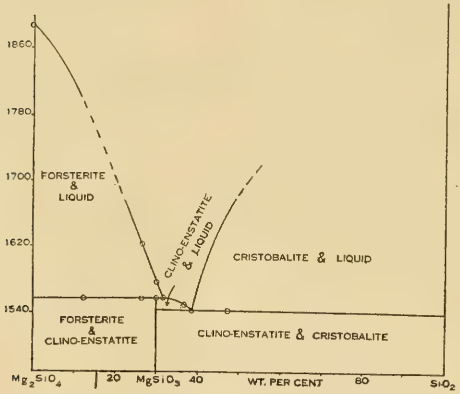


FIG. 3.—Equilibrium diagram of the system, forsterite-silica.

The equilibrium diagram of the system $MgO\text{-}SiO_2$ is shown in Figure 3. A liquid of composition 42 per cent MgO, 58 per cent SiO_2 begins to crystallize with separation of olivine Mg_2SiO_4 and this continues until 1557° when the olivine reacts with the liquid to form the pyroxene clino-enstatite. If the opportunity for reaction[1] is perfect the liquid is completely used up by the reaction and the mass consists entirely of olivine and pyroxene. If, on the contrary, liquid and olivine are not free to continue in intimate contact for any reason, then upon completion of all reaction possible under the circumstances, some liquid will be left over. This will proceed to crystallize in the

[1] The phrase, opportunity for reaction, is used throughout this paper without explanation. It is considered that the various factors involved have been sufficiently discussed elsewhere. The removal of crystals from a part of the liquid by their sinking is a factor limiting the opportunity for reaction as far as that part of the liquid is concerned. And so it is with the formation of a reaction armor about crystals or the squeezing out of liquid from a crystal mesh. Usually the rate of cooling is the fundamental control over these factors and therefore over the opportunity for reaction.

ordinary way giving a mixture of the pyroxene $MgSiO_3$ and silica. We thus obtain a mass consisting of olivine, pyroxene, and silica.

Again it is found that the existence of the reaction relation introduces a flexibility such that different products are obtained with varying opportunity for reaction. Under certain conditions no free silica is formed; under others a little may be formed; and under still others a considerable amount may appear. The compound Mg_2SiO_4 and $MgSiO_3$ may be called a *reaction pair*. By this is meant that crystals of the first compound react with the liquid to produce the second during the normal course of crystallization.

A reaction relation of this latter type may exist between three or more compounds and the compounds, arranged in proper order, may then be said to constitute a *discontinuous reaction series*. An example of this kind of series is given by the system H_2O-K_2SiO_3-SiO_2 as worked out by Morey and Fenner.[1] The equilibrium diagram is given in Figure 4. A liquid of composition A begins to crystallize with separation of K_2SiO_3. This is joined later by $K_2Si_2O_5$ and the two crystallize side by side, the liquid changing in composition along the boundary curve between their fields. At Q_1 the liquid reacts with K_2SiO_3 converting it into $K_2SiO_3 \cdot \frac{1}{2} H_2O$ and if the opportunity for reaction is perfect the whole mass solidifies. On the other hand, if the opportunity for reaction is limited, some liquid Q_1 is left in excess and it proceeds to crystallize along Q_1-Q_2 with separation of $K_2Si_2O_5$ and $K_2SiO_3 \cdot \frac{1}{2} H_2O$. At Q_2 the crystals of $K_2Si_2O_5$ react with the liquid to produce $K_2Si_2O_5 \cdot H_2O$ and solidification is complete if there is complete freedom of reaction. Here again there may be some liquid (Q_2) left over if reaction is for any reason limited and it will proceed to crystallize along Q_2-Q_3 with separation of $K_2Si_2O_5 \cdot H_2O$ and $K_2SiO_3 \cdot \frac{1}{2}H_2O$. At Q_3 the crystals of $K_2SiO_3 \cdot \frac{1}{2}H_2O$ are converted into $K_2SiO_3 \cdot H_2O$. In this case there is always some liquid in excess of that required for the reaction even with perfect opportunity for reaction, but there is more of it when the reaction is limited. The liquid then crystallizes along the boundary between the fields of $K_2SiO_3 \cdot HO_2$ and $K_2Si_2O_5 \cdot H_2O$, with separation of those compounds, until the isotherm of 200° is reached, and if there is no

[1] *Journal American Chemical Society*, Vol. XXXIX (1917), pp. 1173–1229.

further cooling some solution is left that does not crystallize at all.

It is plain from the outline of crystallization given that we have a reaction pair, $K_2Si_2O_5$ and $K_2Si_2O_5 \cdot H_2O$ and also a discontinuous reaction series, K_2SiO_3-$K_2SiO_3 \cdot \frac{1}{2}H_2O$-$K_2SiO_3 \cdot H_2O$. Each member of the series is produced from the preceding member by reaction with the liquid. The series is distinct from a continuous reaction

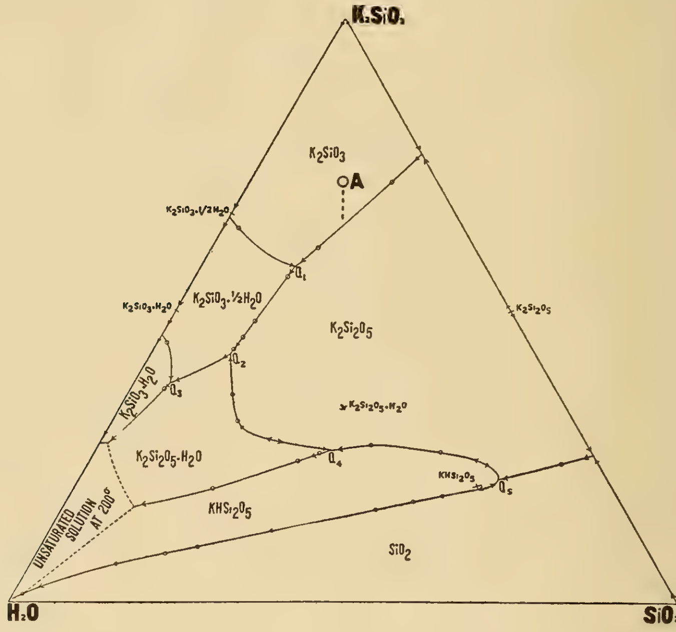


FIG. 4.—Equilibrium diagram of the system, H_2O-K_2SiO_3-SiO_2

series in that changes of composition are discontinuous, taking place in steps and not by insensible gradations as in the continuous series.

The consequences of the existence of this reaction series have been pointed out in the foregoing. Under certain conditions of crystallization we may get simply the three phases K_2SiO_3, $K_2Si_2O_5$, and $K_2SiO_3 \cdot \frac{1}{2}H_2O$. Under other conditions we may get a part or all of a long chain of products including the foregoing three and in addition $K_2Si_2O_5 \cdot H_2O$ and $K_2SiO_3 \cdot H_2O$. Moreover, when crystallization runs far down in the series we may obtain a water-rich

liquid that fails to crystallize at all. The formation of this liquid under such conditions is important in connection with the abundance of analogous liquid in certain types of magma, say, the granitic.

RELEASED MINERALS

A feature of reaction series that is important in its consequences is the fact that a compound, which otherwise would not be formed from a given liquid at all, may, as a result of failure of complete reaction, be stored up in the liquid and appear as a mineral at some later stage. Such a mineral may be regarded as *released* because of the existence of the reaction relation and it is at the same time complementary in composition to the mineral disappearing during reaction. Thus in the case of the reaction pair Mg_2SiO_4-$MgSiO_3$ free silica is released as a result of failure of complete reaction and it is complementary to Mg_2SiO_4.

THE EFFECT OF THE REACTION SERIES ON THE ORDER OF SEPARATION

We have now examined several examples of the manner in which reaction series may render the course of crystallization responsive to external conditions. In another important particular the existence of the reaction series, continuous and discontinuous, causes the process of crystallization to depart from that obtaining in the eutectic system. In the crystallization of the plagioclase feldspars a plagioclase always separates before any other plagioclase that is less calcic. There is no such thing as the separation of calcic plagioclase first from mixtures rich in calcic plagioclase and of sodic plagioclase first (followed by calcic plagioclase) from mixtures rich in sodic plagioclase, as there would be in the eutectic system. And so with the reaction pair and the discontinuous reaction series the higher member of the series always separates before the lower, if at all. We do not have a condition in mixtures of forsterite and clinoenstatite such that forsterite separates first from mixtures rich in forsterite and clinoenstatite first in mixtures rich in clinoenstatite as there would be in eutectic mixtures. On the contrary, forsterite, however small in amount, always separates first.

Thus the existence of reaction series tends to introduce a fixity in the order of crystallization, calcic plagioclase before sodic plagioclase, if at all; forsterite (olivine) before clinoenstatite (pyroxene), if at all; K_2SiO_3 before $K_2SiO_3 \cdot \frac{1}{2}H_2O$ before $K_2SiO_3 \cdot H_2O$.

SERIES WITHIN SERIES

Both the continuous and discontinuous types of reaction series may be much more complicated than the simple examples chosen for illustration. The continuous reaction series may embrace more than two components, and the reaction between liquid and crystals will then be concerned with the adjustment of the relative concentrations of all of the components. Likewise the discontinuous reaction series may consist of any number of members. More than this, any member of a discontinuous reaction series may itself be a continuous reaction series. This case is exemplified by the system diopside-forsterite-silica.[1] Here we have the discontinuous reaction series olivine-clinopyroxene-silica in which the member clinopyroxene is itself a continuous reaction series, that is, a solid solution series. The crystallization of a liquid of this system will illustrate the complexity to which the reaction relation may lead even in this comparatively simple system. The liquid D (Fig. 5) begins to crystallize with separation of the olivine, forsterite. At K the olivine crystals begin to react with the liquid to form clinopyroxene of the composition L, and as the temperature falls the liquid reacts, not only with the remaining olivine crystals to make them into pyroxene, but also with the pyroxene crystals already present to make them more calcic. Thus at F the olivine has been completely changed to pyroxene all of which now has the composition R. In this case, too, lack of opportunity for complete reaction will have an important effect upon the course of the liquid and the kind of crystals produced from it. Failure of reaction will enrich the liquid not only in silica but also in the more calcic pyroxenes.

CRYSTALLIZATION SERIES IN ROCKS

A sufficient number of examples of the reaction relation have been given to illustrate the more important aspects of it. More-

[1] N. L. Bowen, *Amer Jour. Sci.*, Vol. XXXVIII (1914), p. 207.

over the examples have in most cases dealt with members of common rock-forming groups and the prevalence of reaction series of one kind or the other among the rock-forming silicates is indicated by these few examples. The data are not at hand—and are not likely to be for some time—for a quantitative discussion of reaction

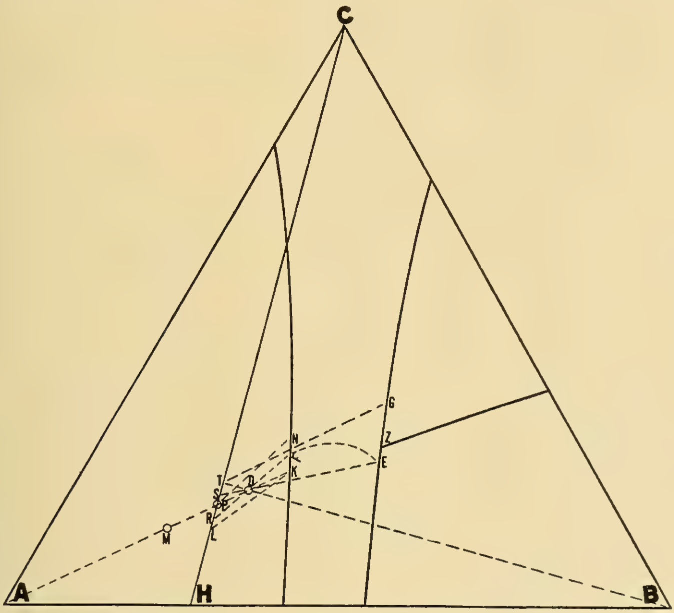


FIG. 5.—Crystallization diagram of the system, diopside-forsterite-silica. *A*, forsterite; *B*, silica; *C*, diopside; *H*, clinoenstatite, and *H–C*, clinopyroxene series.

series in mixtures corresponding to natural magmas. Nevertheless it is believed that much is to be gained from a qualitative consideration of this feature of rock-minerals.

It should be frankly stated that the existence of the reaction relation between two phases in a simple system is no guarantee of the persistence of an identical relation between them in a more complex system. In the case of the phases olivine and magnesian pyroxene, for which such a relation exists in the binary system $MgO\text{-}SiO_2$, it is not unreasonable to expect that the relation might be modified in more complex systems. Actually, however, it is found that the relation persists in all the more complex systems

examined, which fact renders it more likely, but by no means certain, that the reaction relation obtains in magmatic systems.[1] The service rendered by experimental investigation, so long as it is confined to a limited number of components, must lie in its indicating where a reaction relation is to be expected. We are, moreover, instructed as to what we may expect in the way of indications of reaction and thus enabled to extend our inferences to phases not formed under laboratory conditions. This brings us to the question of the criteria of the reaction relation.

A criterion of the reaction series, common to both the continuous and discontinuous type, and serving to show their fundamental likeness, is simply the tendency of one mineral to grow around another as nucleus. In the case of the continuous series this is commonly known as zoning of mix-crystals and in the discontinuous series as the formation of reaction rims, coronas, etc. Thus we have plain evidence of this kind, from a wide range of rocks, that that the plagioclases constitute a continuous reaction series and that pyroxene, amphibole, and mica form a discontinuous series. The development of these special structures is, however, dependent on particular conditions of consolidation and the lack of such structure in an individual case should not be regarded as indicating a lack of the reaction relation in that case. It must be, in part, from a general survey of mineral relations in igneous rocks that the reaction series are deduced.

Fortunately the continuous reaction series are easily picked out, for the mere existence of solid solution or variability of composition in a crystal phase is sufficient to establish that phase as a continuous reaction series. Their number is legion, all the important igneous rock minerals with the single exception of quartz being members of solid solution series. The detection of the discontinuous reaction series is not always so easy, and the element of judgment enters to some extent.

As an example of the information to be obtained on this point from a general survey of an igneous sequence let us reproduce a

[1] Vogt believes there is no reaction relation but a eutectic relation at higher pressures between olivine and pyroxene. *Jour. Geol.*, Vol. XXIX (1921), p. 528.

table given by Harker showing the mineral relations in the sequence at Garabal Hill.[1]

TABLE I

MINERAL AND ROCK SEQUENCE AT GARABAL HILL (AFTER HARKER)

	1. Iron Ore	2. Olivine	3. Augite (diallage)	4. Brown Hornblende	5. Green Hornblende	6. Biotite	7. Plagioclase	8 Orthoclase	9. Quartz
A. Olivine-diallage-rock	+	+	+	+	–	–	–	–	–
B. Biotite-diorite	+	–	–	–	+	+	+	–	–
C. Hornblende-biotite-granite	+	–	–	–	+	+	+	+	+
D. Porphyritic biotite-granite	+	–	–	–	–	+	+	+	+
E. Eurite vein	+	–	–	–	–	–	+	+	+

It will be noted that the minerals *appear* in a certain order, as they might in a system where simple eutectic relations prevailed, but they also *disappear* in a similar order, a feature that is altogether foreign to a eutectic system. In a eutectic system no mineral ever disappears.[2] The first-formed mineral is simply joined by another, the pair by a third, and so on until all the minerals appear together in a final eutectic product. Very different from this is the condition actually found, namely, the disappearance of minerals in the order in which they appear which is of the very essence of the reaction series.

Upon examination in detail it is found that 2, 3, and 4 disappear in B, 5 disappears in D, and 6 in E. From this we conclude that these phases bear a reaction (not a mere subtraction) relation to the liquid and that, as a result of the reactions, phases appearing later are formed. We arrive at the definite conclusion that 4, 5, and 6 constitute a reaction series and at the same time note indications that they are but a part of a series containing more members.

[1] *The Natural History of Igneous Rocks*, 1909, p. 131.

[2] A case of simple inversion without change of composition would require to be excluded from this statement, but it has no importance in rocks at any rate.

By piecing together the information to be obtained from the examination of such sequences and observation of the structural relations of the minerals a conclusion as to the reaction series in rocks is to be arrived at. Without going into detail as to the evidence, an attempt is made below to arrange the minerals of the ordinary subalkaline rocks as reaction series. Neither rigid accuracy nor finality is claimed. It is regarded merely as a framework upon which others may build, making such modifications and additions as may be found necessary.

TABLE II

REACTION SERIES IN SUB-ALKALINE ROCKS

```
olivines                (spinels)
   ↘                              calcic plagioclases
     Mg pyroxenes                      ↙
          ↘                    calci-alkalic plagioclases
         Mg-Ca pyroxenes              ↙
               ↘           alkali-calcic plagioclases
              amphiboles            ↙
                   ↘alkalic plagioclase
                  biotites         ↙
                        ↘        ↙
                     potash feldspar
                           ↓
                       muscovite
                           ↓
                         quartz
```

Beginning at the upper end of the series in the more basic mixtures we have at first two distinct reaction series, the continuous series of the plagioclases and the discontinuous series, olivines-pyroxenes-amphiboles, etc. As we descend in these series, how-

ever, they become less distinct, in the aluminous pyroxenes and amphiboles a certain amount of interlocking begins and they finally merge into a single series.[1] This is expressed diagrammatically by a convergence of the series, with a dovetailing of the mineral names at first, and finally a joining of the two series by the arrows converging upon potash feldspar. Just where the two series merge completely is more or less a question, but it is given closely enough for our present purpose in the figure.

That the series, olivines-pyroxenes-amphiboles-biotites, constitutes a reaction series is well attested in many rock varieties. By this is meant that liquid reacts with olivines to produce pyroxenes, with pyroxenes to produce amphiboles, and with amphiboles to produce biotites. In the continually increasing water content of the series it is related to the series K_2SiO_3-$K_2SiO_3 \cdot \frac{1}{2}H_2O$-$K_2SiO_3 \cdot H_2O$. The continuous reaction series of the plagioclases is perhaps the best understood series of rock minerals. This is fortunate, for the series happens to be of particular importance in that it runs through a wide range of conditions and compositions in the rock series. We simply have a continual enrichment of the liquid in alkaline feldspar with the separation of the potash variety of alkaline feldspar as a separate phase when it has exceeded its solubility in the plagioclase mixture. With the formation of potash feldspar in the one series and of biotite in the other, the two series are now so intimately intermingled as to constitute a single series.

There is a little of the nature of eutectic crystallization in the crystallization series given in the foregoing. At early stages and as between the two series there is some suggestion of the eutectic relation in that a member of one series lowers the melting "point" of a member of the other series. Moreover the one or the other begins to separate first according to which is present in excess over certain fixed proportions. There the analogy with eutectic crystallization ends for the simple reason that there is no eutectic, no inevitable end-point where final solidification must take place when the liquid has attained a certain composition. The minerals

[1] The two series are bridged at the very outset by spinel but this has, on the whole, no great practical importance.

have a reaction relation to the liquid, not a mere subtraction relation. Each separated mineral tends always to change into a later member of the reaction series. This change of composition is effected by reaction with the liquid, and according to the opportunity for reaction the liquid is entirely used up, in some cases sooner, in others later, and only then is solidification complete.

Thus we see that rock series cannot be partitioned off into such divisions as gabbro, diorite, etc., each having a eutectic of its own. All of these belong to a single crystallization series, to a single polycomponent system, which is dominated by reaction series.

Even after what is ordinarily termed complete consolidation of the rock many changes of a reaction nature may occur between the minerals. Usually a small amount of liquid is a factor in these changes which are commonly described under the head, metamorphism. Certain aspects of these changes have been described by V. M. Goldschmidt in a paper on metasomatism.[1] It is important to note in the present connection that metasomatic reactions are not confined to the metamorphic stage but are, as we have seen, a constant feature of the whole process of crystallization of the magma. Eskola has presented evidence for believing that, at times, the original crystallization of a magma may itself take place under the conditions that are ordinarily prevalent during metamorphism. The rock then presents a "mineral facies" identical with that of a metamorphic rock of the same composition formed under the same conditions. Totally different reaction series would be concerned in the crystallization of these rocks and we have not gone far toward an understanding of these, though Eskola has done much to set us on our way.[2] The variation of conditions necessary to produce different facies is of a different order of magnitude from the variation of conditions here considered. This is largely a variation of the rate of cooling and we are here concerned mainly with the diverse rocks in the common and definitely established sequence that can be produced under the conditions of his diabase facies principally. With adequate

[1] *Economic Geology*, Vol. XVII (1922), p. 105.

[2] P. Eskola, *Norsk Geologisk Tidskrift*, Vol. VI (1920), pp. 143–94.

fractionation under conditions of slow cooling we may, however, have such concentration of mineralizers and consequent lowering of consolidation temperatures that conditions correspond to those of other facies.

EMPIRICAL RULES REGARDING ORDER OF CRYSTALLIZATION

As the result of a most extensive knowledge of the relations of minerals in rocks Rosenbusch formulated certain rules regarding the order of crystallization. When petrologists began to think of the crystallization of rocks in terms of eutectics these rules seemed to be quite at variance with theory, for this stated that those minerals should separate first that were in excess over eutectic proportions. To reconcile this with Rosenbusch's rules giving a fixed order of crystallization was a very difficult problem, and yet it was conceded that his rules represented the facts in very remarkable degree. In the light of the reaction principle no such difficulty is encountered. It is characteristic of the reaction series, as we have already seen, that however small an amount of any member may form, it always forms before a lower member of the series. In so far as reaction series control the crystallization of rocks they tend to produce a fixed order of crystallization.

Another generalization concerning the order of crystallization came from the French school of petrology. It was that the minerals separate in the order of their fusibilities, the least fusible first. This generalization, too, in the light of the doctrine of eutectics seemed to be quite absurd, but here again there is a very considerable accord with the facts. Such substances as spinel and chromite are among the most refractory materials known. Magnesian olivine has the highest melting-point of the common rock-forming silicates. The more magnesian pyroxenes stand next in the list, with the more calcic feldspars about on a par with them. The more complex pyroxenes, the amphiboles, and in particular the more alkalic feldspars are lower still. And this list corresponds very satisfactorily with the order of separation of the minerals from magmas. Again we are dealing with a tendency that is introduced by the presence of reaction series. It is a familiar character of a reaction series of the continuous type that the higher melting

members should crystallize first (witness the plagioclases), and there is a no less distinct tendency in this direction in the discontinuous reaction series.

This explanation and vindication of the doctrine of the French school is not, however, to be regarded as a proposal that we should reverse the attitude arising from eutectic considerations and accept unreservedly the statement that minerals separate in the reverse order of their fusibilities. There are too many obvious exceptions to such a rule. However, these exceptions are themselves such as might be anticipated in a system dominated by reaction series. We have seen on an earlier page that certain minerals that may be called released minerals may appear in such a system. It is apparently minerals that belong in this category that constitute the more notable exceptions. The principal of these is quartz. It is a released mineral of the reaction, olivine-pyroxene and no doubt has a similar relation in the reaction, potash feldspar-mica, a sort of hydrolysis requiring an adequate concentration of water. It is a mineral of high melting-point but separates very late—a fact that is to be connected with its character as a released mineral. In other words, it may be regarded as not actually present in the liquid at an early stage, but as released later in consequence of the reactions mentioned.

Some minerals may separate early when intrinsically present and may also appear as released minerals at later stages. Magnetite is a particularly good example. It may separate very early from a gabbro and it may be formed very late as a result of, say, the pyroxene-hornblende reaction and in particular of the mica-feldspar reaction.

PROGRESS TOWARD AN UNDERSTANDING OF REACTION SERIES IN MAGMAS

At this place it may be well to point out where we are in particular need of increased knowledge in order to understand the exact nature of the reactions occurring. It will be noted that each member of the discontinuous reaction series, olivines-pyroxenes-amphiboles-biotites, is itself a continuous reaction series. Of the olivines and the pyroxenes we know a fair amount, but practically

nothing is known as to the details of the amphiboles or the biotites as reaction series, and this means not merely their possible range of composition but also how those compositions are arranged in the series. The continuous reaction series of the plagioclases occupies a more conspicuous place than the other continuous reaction series, not merely because we know more about it, but because, as already pointed out, it enters into the rock series through a much wider range of conditions. Of the plagioclases we require to know how the potash feldspar enters into their make-up and, in the present connection particularly, at what stage in its concentration the potash molecule must appear as a separate phase. We require to know, too, the exact composition of pyroxene that forms by reaction from olivine of a certain composition, the exact composition of amphibole that forms from a certain pyroxene, and so on. These are questions on which much light may be shed by systematic equilibrium studies in synthetic minerals and by careful separation and analysis of associated minerals in various rock types. Studies of this kind are now being carried on at this Laboratory by Aurousseau on olivines, by Washington and Merwin on pyroxenes, and by Buddington on melilites. Eskola points out the importance of such work on the natural minerals, referring to it under the special name, facies petrology.[1] The results of these and kindred investigations may be profitably regarded in the light of their bearing on the reaction principle, for in their manifold details they are likely to prove excessively wearisome unless considered in relation to some such co-ordinating principle.

REACTION SERIES AND MAGMATIC DIFFERENTIATION

As the information gained from such studies of reaction series accumulates, our knowledge of igneous rock differentiation should increase conspicuously, for the reaction principle is the very life-principle of differentiation. We have seen, in our examination of the simple systems used to illustrate reaction series, how the existence of the reaction relation lends a flexibility to the behavior of a cooling liquid, renders it capable of giving different products

[1] P. Eskola, "The Eclogites of Norway," *Videnskapsselskapets Skrifter I. Math. Naturv.*, Klasse No. 8 (1921), p. 6.

according to the conditions under which it cools. This is equally true of the complex reaction series that dominate the crystallization of magmas an outline of which, for the subalkaline magmas, is suggested in Table II. As a result of the existence of the reaction relations there indicated, it may come about that a magma precipitating olivine may, at a later stage, react with the olivine and convert it into pyroxene, and, according to the extent to which controlling conditions facilitate the reaction, the whole future course of the magma is modified. If conditions are particularly favorable the reaction may be complete and the olivine may disappear, its place being taken by pyroxene. The liquid then cools further with deposition of later members of the crystal series. If conditions are not so favorable some olivine may be left unchanged and, in consequence, a somewhat different liquid is left to pass on down the crystal sequence. So it is with the reaction, pyroxene-amphibole. Not only that, but within each mineral group the reactions may be variously facilitated under different conditions. This is true not only of the members of the olivine-pyroxene-amphibole series but also of the plagioclase series, and the liquid may be entirely used up by reaction, sometimes earlier, sometimes later. It need not be surprising, therefore, that the differentiates derived from a gabbro magma may vary both in scope and quality. We may have only gabbro and diorite in one case, but a longer sequence including granite in another. We may have a potassic granite in one case and a sodic granite in another. Rapid crystallization at an early stage, with subsequent slowing-up, seems to bind up much of the potash feldspar in the early formed plagioclase and give a sodic granite. On the other hand slow cooling throughout seems to avoid this factor and give potash granites. Too little is known as yet of the details of the various reaction series to make possible any very definite statements on these points.

In offering an outline of crystallization series in rocks (and therefore of differentiation) the list has been carried only as far as the constituents of granite. This should not be interpreted as indicating that there is anything final about the granite with respect to differentiation series. We have seen in the system K_2SiO_3-SiO_2-H_2O that when any mass is cooled to 200° and no farther there will commonly be a liquid left over that never crystallizes.

The composition of this liquid lies at some point on the 200° isotherm. If the cooling were continued to 100° and no farther there would again be liquid left whose composition would be represented by a point on the 100° isotherm, and this liquid would never crystallize. And so it would be for any temperature except some negative temperature at which the water itself would appear as ice.

A similar condition will prevail in the aqueous system represented by magmas. The cooling of rocks is always limited by the temperature of their surroundings. There is always a liquid left that does not crystallize and it is probable that to the very last the rock constituents bear a reaction relation to this liquid.

In this connection the behavior of liquids crystallizing along the boundary Q_5-H_2O (Fig. 4) may be instructive. At the higher temperatures crystallization consists of the simple separation of both $KHSi_2O_5$ and quartz, but at lower temperatures $KHSi_2O_5$ separates and quartz redissolves, or, better, the liquid reacts with quartz, converting it into $KHSi_2O_5$. If the reaction is not free to take place the liquid leaves the boundary curve, passes into the $KHSi_2O_5$ field, and thereafter only $KHSi_2O_5$ separates from it, no quartz. Thus we have a reaction relation between liquid and crystals at the very latest stages and, in consequence of it, alternative behavior of the liquid.

There are some indications that in granitic liquid at the pegmatite stage, more or less similar conditions prevail. Quartz may react with liquid to produce feldspar and sometimes the graphic structure may be a result of this reaction (replacement). Why replacement should produce graphic structure in some instances and not in others is not apparent, but the possibility should be considered that graphic structure may often be the result of replacement both in rock minerals and in ore minerals. The graphic intergrowth of spinel and pyroxene seen in certain rocks can scarcely be interpreted otherwise than as due to reaction.[1] Experimental work on systems involving these phases shows pretty definitely that anything suggesting a eutectic relation between spinel and pyroxene is not to be entertained.[2]

[1] W. N. Benson, *Jour. Proc. Roy. Soc. N. S. Wales*, Vol. XLIV (1910), p. 521.

[2] Rankin and Merwin, "The Ternary System MgO-Al_2O_3-SiO_2," *Amer. Jour. Sci.*, Vol. XLV (1918), pp. 301–25; also Olaf Andersen, "The System: Anorthite-Forsterite-Silica," *Amer. Jour. Sci.*, Vol. XXXIX (1915), p. 437.

If a reaction of the kind suggested (involving quartz, feldspar, and mica molecules) is a definite feature of pegmatitic granite it is possible that failure of reaction may produce a liquid deficient in silica, just as such a liquid is produced in the system above. From this liquid feldspathoid may be deposited instead of some of the feldspar. Thus it is possible that alkalic rocks may, in some cases, be formed as a result of the reaction relation among the minerals noted. Foye has noted a very intimate relation between the granite pegmatites and nephelite syenite of Haliburton, Ontario.[1]

NOTE.—Since the foregoing was written it has been demonstrated by Morey and Bowen that leucite and orthoclase constitute a reaction pair with quartz as a released mineral. The importance of the reaction principle in connection with the origin of some alkaline rocks is confirmed by these facts but the full significance cannot be discussed here.

SUMMARY

Petrogenic theory has passed beyond the stage where the conception of eutectics can longer be regarded as of any considerable service. Experimental investigations and the study of the rocks themselves, in the light of such investigations have made it clear that the eutectic relation is unimportant but that another relation between liquid and crystal phases, here called the reaction relation, is of fundamental significance. The ordinary solid solution series such as the plagioclases may be regarded as a *continuous reaction series* because during crystallization each member is produced from an earlier member by reaction with the liquid, the variation of composition being continuous. There are also *discontinuous reaction series* exhibiting related characters but with discontinuous changes of composition. The series olivine-pyroxene-amphibole-mica is a prominent example among the rock-forming minerals.

On the basis of these considerations the minerals making up the rocks of an igneous sequence can be arranged as reaction series and it is the existence of such series that controls the crystallization and differentiation of the rocks of the sequence. Even the graphic structure, usually regarded as a eutectic structure, is probably to be considered the result of reaction between the phases in many examples.

January, 1922

[1] *Amer. Jour. Sci.*, Vol. XL (1915), p. 436.

AN OUTLINE OF THE PHYSIOGRAPHIC HISTORY OF NORTHEASTERN ONTARIO[1]

W. H. COLLINS
Canada Geological Survey, Ottawa

The region here referred to as northeastern Ontario is one about 250 miles square, lying between Lake Superior and the Quebec boundary and reaching from Lake Huron north to the Transcontinental Railway. Its topography has been described so many times in reports of the Geological Survey and of the Ontario Bureau of Mines that no extended account of it is needed in this place. The region is referred to by geologists and topographers as a glaciated peneplain. As a matter of fact it is a hilly country and only conveys an impression of flatness when a large area is seen at one time. Viewed from the top of one of the more commanding hills the horizon appears as an even line and the intervening hills can be seen to stand at about the same elevation. The rivers have slopes of only 5 to 10 feet a mile, and the highest and lowest points on the railways which cross the region are 1,350 and 600 feet above sea.

This condition holds true for most of northeastern Ontario. There are a few places, however, where the relief is greater, and where significant traces remain of a former topography of more rugged character. There is, for example, one hilltop, about 40 miles west of Sudbury, from which one can see, on a fine day, a line of white hills on the southern horizon that certainly remind one of mountains. These are the Lacloche Mountains, to which further reference will be made. It also requires considerable scientific faith to acknowledge the wild country bordering Lake Superior as plainlike or nearly plainlike.

In the case of a true plain, like the Mississippi basin, or the western plains of Canada, the impression of tranquillity conveyed by the landscape is borne out by the rocky structure underneath.

[1] Read before Section E, American Association for the Advancement of Science, December 27, 1921.

The rock formations are all sediments, deposited by the subdued agencies of water or of wind. They lie in horizontal beds, free from stress.

The mild topographic aspect of most of northern Ontario might lead one to expect somewhat the same undisturbed condition underground. This is not found, however. It is not asserted here that some of the rock formations are not flat-lying or nearly so. Some of them are; but the prevailing condition is quite different. Characteristically, the stratified formations of northern Ontario are folded, twisted, sheared, and broken in the most extraordinary manner. They spring from deep underground in arches that are abruptly truncated by the surface of the peneplain. In places they have been broken by faults so great that the two sundered parts of a formation, that once lay face to face, are now found from a few hundred feet to a mile apart. They are cut by dikes and sills of rocks that were once molten, and a large share of the present surface of the region is now underlain by batholithic masses of granite, once molten, a hundred miles or so in diameter, and of unknown depth. The condition is one of suspended geological turmoil of incredible magnitude and violence.

There is something dramatic and stirring to the imagination in this contrast between the mild landscape of the present northern Ontario and the evidence of telluric convulsion that lies just beneath it; a contrast which impels one to speculate about the cause of this violence, in what manner it expressed itself at the surface of the earth, and what have been the processes of change between then and now.

The characteristic geological features of this region, as contrasted with those of a true plain, are the extreme deformation of the stratified formations, and the presence of igneous formations, particularly the batholiths of granitic rocks. If one studies a geological map of North America (Fig. 1), it is soon apparent that, outside of the great Precambrian Shield region, to which northern Ontario belongs, the greatly folded and faulted rocks are confined to the mountain regions—the Western Cordillera and the Appalachian Mountains along the Atlantic Coast. It can be seen at the same time that great granite masses, the batholiths, are present

in these mountain regions, and nowhere else in the continent, except, of course, in the Precambrian Shield.

This conjunction of batholithic intrusions with mountain systems is no new observation. It has been long noted and there

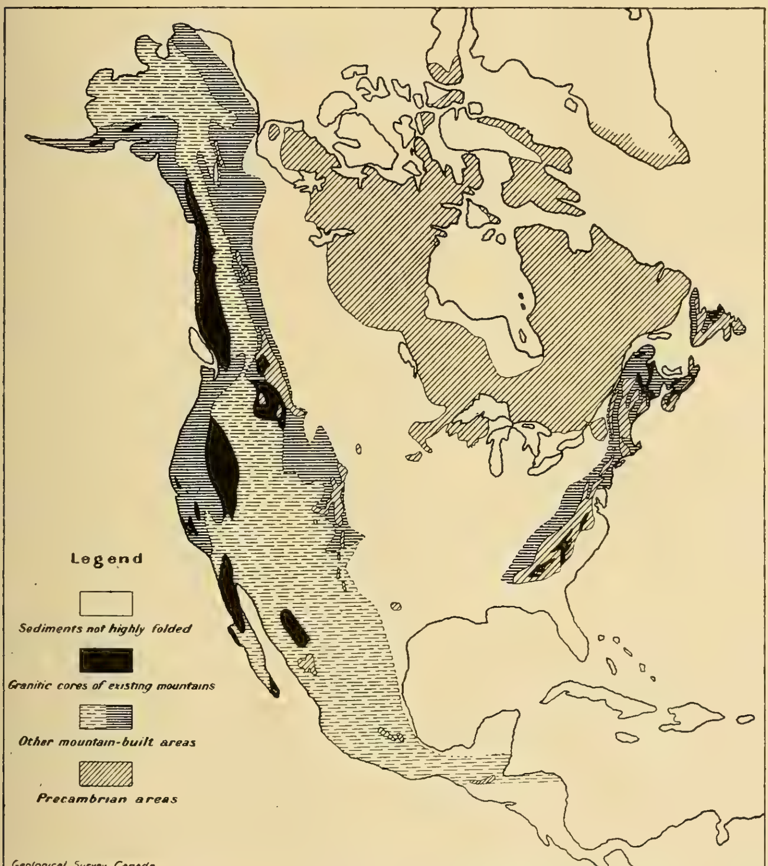


FIG. 1.—Map of North America to show the distribution of batholithic intrusions in relation to mountain-building.

has been much speculation as to the nature of the association—whether the compression and upheaval of the earth's crust caused the igneous invasions or whether the latter were causes or mere concomitants of mountain-building. Nor has the analogy between

the deformed strata and intrusive batholiths in mountain regions and in the flat, Precambrian Shield, been overlooked; but the apparent total absence of actual mountains in the Precambrian Shield, as well as its enormous area, exceeding that of any known mountain system, have led geologists to accept the theory of Precambrian mountain-building with reservations, or even to prefer the explanation that the Precambrian Shield is part of the original crust of a once molten world.

Let us compare the mountains of North America in respect to their ages, their topographic aspects and the abundance in them of batholithic rocks. The accompanying illustration (Fig. 2), compiled by J. F. Wright, of the Geological Survey, Ottawa, shows a series of representative cross-sections through the Rocky Mountains, the Coast Mountains, the Appalachians, the stumps of the ancient Acadian Mountains of Nova Scotia, and through a part of the peneplain of northeastern Ontario. The sections are arranged in order of age from youngest to oldest, are all referred to sea-level and drawn to the same horizontal and vertical scales, the relief being exaggerated twenty-one times.

The Rocky Mountains, which date from early Tertiary time, reach elevations of 10,000 to 12,000 feet, have an extremely sharp profile and reveal no batholithic intrusions, although some distance south of the line of section the Ice River syenite mass does reach the surface. The Coast mountains, of Jurassic age, reach about 7,000 feet above sea, and more than one-third of the section is of batholithic granitic rocks. These mountains are scarcely less sharp in profile than the Rockies; but that is due to the fact that they have been elevated twice and are now being carved a second time. The Appalachians were formed about Permian time, and have suffered erosion for a correspondingly longer time than the Coast and Rocky mountains. They reach only 2,800 feet above sea, have a comparatively gentle skyline, and erosion has laid bare a larger proportion of their granite core. The Acadian Mountains can be called such only in a genetic sense. They possess a relief of only a few hundred feet, and their granite core is freely exposed. They are the barely recognizable roots of mountains, and not more deserving of the designation than those shown in the next and last section.

Reference was made in the first paragraphs of this paper to Lacloche Mountains, south of Sudbury, as one of the topographic

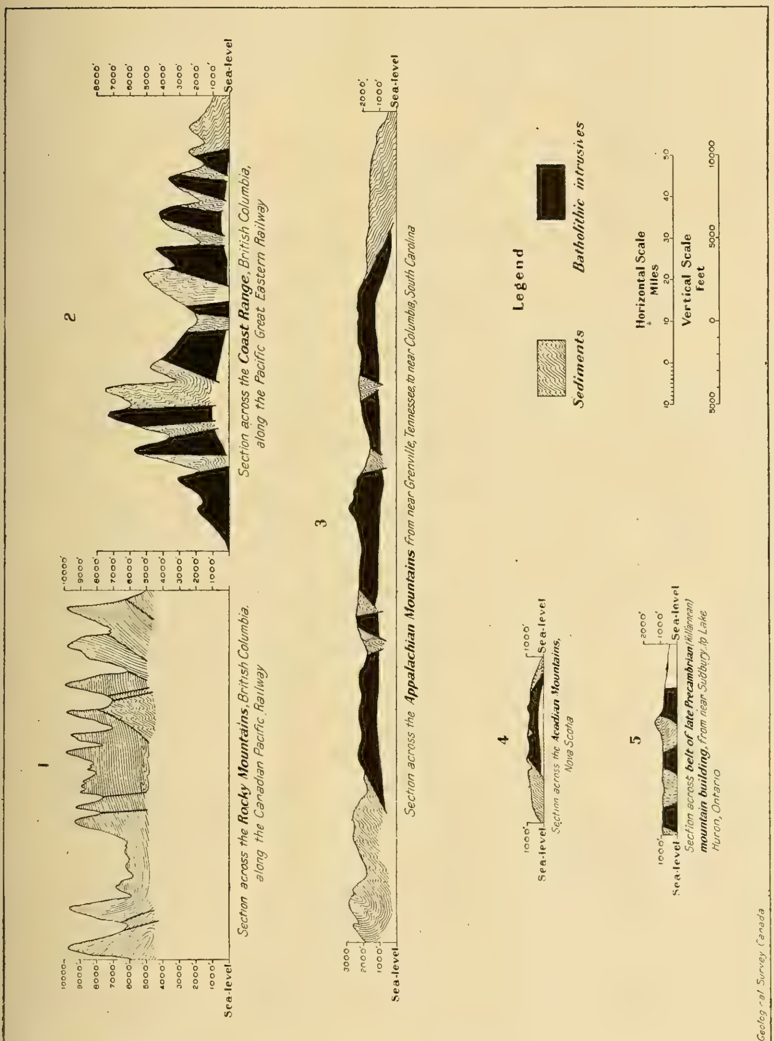


Fig. 2.—Series of cross sections of the mountain chains of North America to show the progressive effect of erosion in laying bare batholithic intrusions, and to show also the genetic relationship between mountain-building and the geology of the Precambrian field.

features that can scarcely be included as part of the Precambrian Shield peneplain. They rise in a solid, broad-based range 60 miles long and as much as 800 feet above the surrounding country.

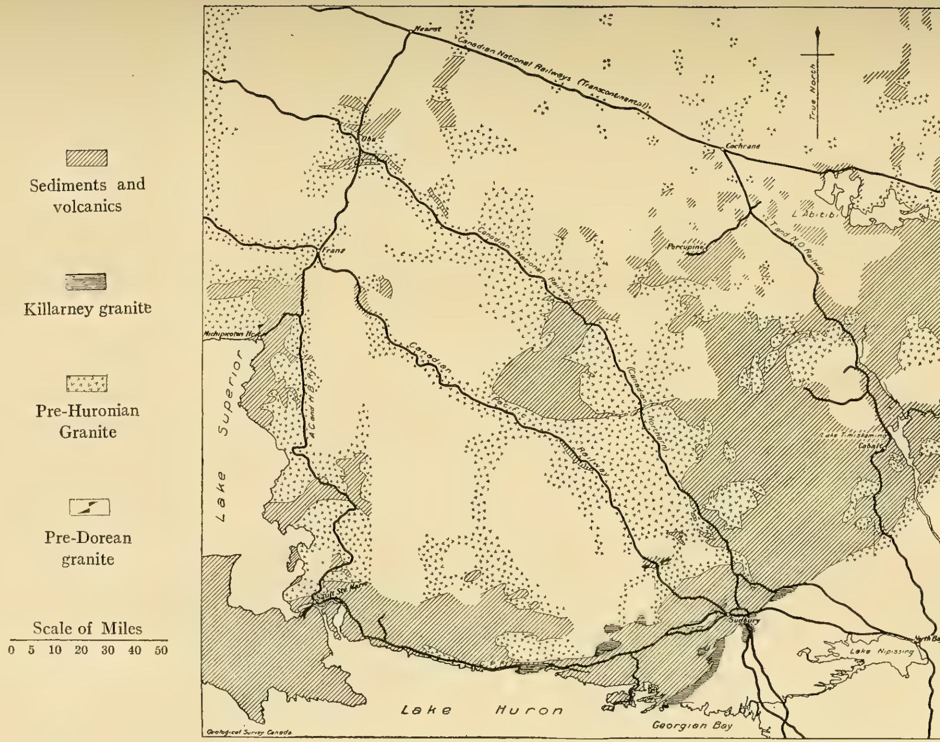
Their mountainous aspect is enhanced by the fact that they consist of white, Lorrain quartzite and, when seen from any considerable distance, look as if they were covered with snow. The last of the five cross-sections in Figure 2 is through Lacloche Mountains. The sediments forming these mountains are Precambrian (Huronian), and the intrusive granitic batholiths are late Precambrian (Killarney).

Figure 2 has been introduced for the purpose of demonstrating that the associated phenomena of regionally deformed strata and batholithic intrusion are results and criteria of mountain-building and that by sufficiently protracted erosion a mountain system may be reduced to a peneplain having the topographic appearance and geological characteristics of northern Ontario. Endeavor will now be made to apply these criteria to the Precambrian Shield and to outline the chief events in the physiographic history of the northeastern part of Ontario, proceeding from the present as far back in time as the geological record has been interpreted.

Figure 3 shows the distribution of the essential geological elements in northeastern Ontario with which this thesis is immediately concerned. It also contains a tabular record of the geological periods. Periods not represented by rock formations in the region are shown in brackets. The larger spaces represent gaps in the record of intervals of erosion, and an attempt has been made to indicate, conservatively, by the size of the space, the length of time unrepresented by rock formations.

Let us take that part of the record from the Ordovician period to the present. Only a few of the series of formations are present—the Ordovician, Silurian, part of the Devonian, a little of what Mr. Keele regards as Cretaceous,[1] and the Pleistocene. All these formations lie horizontally or dip at very low angles. The Ordovician, Silurian, and Devonian are limestones, shales, and sandstones that contain fossil remains of marine animals. The Cretaceous contains beds of lignite and was presumably laid down on land or very near land. The Pleistocene consists of glacial bowlder clay and stratified clays and sands laid down in postglacial lakes. The careful studies of glacialists, Coleman, Johnston, Taylor, and others, have

[1] *Summary Report, Geol. Surv., Can.* (1919), Part G.



Geological Column

Era	Period
Quaternary	Recent Pleistocene
Tertiary	(Pliocene) (Miocene) (Oligocene) (Eocene)
Mesozoic	Cretaceous (Jurassic) (Triassic)
Palaeozoic	(Permian) (Pennsylvanian) (Mississippian) Devonian Silurian Ordovician (Cambrian)
	Keweenawan
	Animikie (Whitewater)
Huronian	Cobalt Bruce
Pre-Huronian	Period of Sedimentation (Timiskaming Sudburian, etc.) Period of Volcanism Keewatin?) Period of Sedimentation (Dore series) Period of Volcanism

FIG. 3.—Map of Northeastern Ontario to show the known distribution of the batholithic intrusives (Painters) which are of three distinct ages and are related to three corresponding processes of mountain-building.

shown that the northeastern part of the continent, released from its load of ice, has readjusted itself, since the Glacial period, by gentle rising and tilting movements. There are no violently disturbed formations among these. There can be no doubt, then, that from Ordovician time until now northeastern Ontario has experienced only gentle oscillations in level and shallow marine submergence.

Let us take next the section of time from the beginning of the Bruce period until the end of the Keweenawan. This time is represented by a blanket of sediments aggregating over 30,000 feet in thickness, in the southern part of the region of northeastern Ontario, but thinned out to nothing by erosion, toward the north. The Bruce series is in part a land formation, and was for the remaining part apparently laid down at the edge of a continent; the Cobalt and Keweenawan series are both continental. In the northern part, these formations (represented by the Cobalt series) lie almost flat, or in open folds. Consequently it can be said with assurance that from the time of their deposition this northern part of the region has experienced no movements but those of rise and fall and mild compressional folding. Tracing these sediments southward, however, they become progressively more closely folded. South of a line drawn eastward and westward through Wanapitei Lake, the folds are tight and have a definite eastwest, axial course. Small masses of granite, intrusive in all these formations, appear at Cartier, at Sudbury, and at other points and, finally, in a line running northeasterly from Killarney, the Bruce series and later Precambrian sediments are abruptly truncated by a granite batholith of undetermined extent. How far southward this condition extends cannot be ascertained, because, from Lake Huron southward, the Precambrian formations are covered by the horizontal Palaeozoics.

It is abundantly clear that—if the associated phenomena of close regional folding and batholithic invasion indicate mountain-building—in late Precambrian time the southern part of the region shown on this map was compressed to form a system of mountains. These mountains occupied only the southern part of northeastern Ontario. They extended west along the south side of Lake Superior

at least as far as Duluth. How far eastward they extended is not known, nor, owing to the cover of Palaeozoic sediments, how far south.

Between Keweenawan and Ordovician time these late Pre-cambrian (Killarnean) mountains were worn down to a condition probably not greatly different from that of the Adirondacks today, and certainly greater relief than the Lacloche Mountains of today, for these latter have since endured additional erosion from Palaeozoic time onward. A few peaks of the Killarnean Mountains now project through the Palaeozoics on Manitoulin Island; and bore-holes that have been made near by in the search for oil indicate a submountainous local relief of more than 800 feet in the floor upon which the Ordovician formations were laid.

Let us next consider the period of time that elapsed from the commencement of deposition of the Doré sedimentary series until the Timiskaming series and Sudbury series were completed. The Doré series is almost certainly of continental origin. It is thought to have been deposited under conditions like those which governed the deposition of the silts and gravels in the interior plateau of British Columbia. The Keewatin volcanics are believed by some geologists to be of submarine origin, owing to the abundance among them of ellipsoical greenstone; but the writer can find no evidence to support this view. It appears, rather, that they were deposited on land and in small bodies of water. Recent studies of the Timiskaming series by Mr. H. C. Cooke[1] indicate a continental origin for this series also. Judging by the extremely variable thickness of the sediments throughout this group, their coarse texture, and apparently local deposition, the region may have been one of considerable topographic relief during the entire time.

Except in the southern portion of northeastern Ontario, these formations are extraordinarily folded, schistified and faulted, and invaded by granite batholiths of huge size. In fact, they are represented now only by irregular patches which were down-folded low enough to escape erosion. If intense regional disturbance and batholithic invasion indicate mountain-building, it must be con-

[1] "Kenogami Lake and Larder Lake Areas," *Geol. Surv., Can.*, Memoir in course of publication.

cluded that following Timiskaming time the whole region, shown in Figure 3, was mountain-built. The southern portion was long afterward involved in the Killarnean mountain-building and, in that part, any evidence of this earlier orogeny was pretty completely demolished; but there is little doubt that the older mountains extended over the whole region.

Between the finish of Timiskaming sedimentation and the commencement of the Bruce period these older, pre-Huronian mountains must have been uplifted, carved, and completely destroyed, for the Bruce series lies upon a peneplained surface evidently quite as maturely eroded as the surface of today. The evidence for this has been discussed at length in various Geological Survey reports,[1] and need not be repeated. Attention need be directed here only to the length of time required for this complete physiographic cycle; the Appalachian Mountains, which are not yet nearly so completely leveled, have existed since Permian time.

Just as the Killarnean mountain-building demolished in the southern part of the region the evidence of earlier geological history, so it might be expected the pre-Huronian mountain-building, which extended over the whole region, would have obliterated all of the geological record anterior to the deposition of the Doré series. This is not wholly the case. When the Timiskaming series was first described by W. G. Miller,[2] he noted that it contained granite pebbles. Many years before, Logan noted the presence of granite bowlders in the Doré series, though, at that early stage in Canadian geological work, he could not be sure of the position of this series in the geological scale. These granite inclusions in the oldest known sediments have afforded ground for much speculation regarding the nature of the surface from which they were derived, and upon which they were deposited.

It was not until 1920 that the ancient granite which supplied these pebbles was identified *in situ* beneath the Doré series, near Michipicoten Harbor. At that place the Doré series lies tilted at an angle of 50° or more against a basement of older rocks, from

[1] M. E. Wilson, *Geol. Surv., Can.*, Memoir No. 39; W. H. Collins, *op. cit.*, Memoir Nos. 33, 95, and another not yet published.

[2] *Ann. Rep. Ontario Bureau of Mines*, Vol. XIX, Part 2, p. 62.

which it derived most, if not all, its pebbles and bowlders. This basement is in part composed of schistose volcanics and in part of gray granite. Its extent, away from the Doré series, has not been worked out and will be very difficult to determine; but there is quite enough to indicate that a third granite, older than the Killarney and the pre-Huronian granites, exists, and had been laid bare in large volume in pre-Doréan time.[1] Was this pre-Doréan granite indicative, like its successors, of a third mountain-building activity that took place in a time too remote for the mind to comprehend?

Regarding the physiographic conditions governing the deposition of the Doré series the authors of the report mentioned speculate as follows:[2]

> The writers are inclined to visualize Michipicoten district at the commencement of Doréan time as a region of rugged relief and waning volcanic activity. During early Doréan time this land surface, devoid of vegetation, was eroded rapidly, some of the deep-seated granite masses being uncovered to provide the great quantities of granite pebbles and bowlders found in the Doré conglomerate. The rude granite and porphyry conglomerate and associated formations in the lower part of the series were formed nearly in place by rock disintegration, with a consequent aggradation, or wearing down of summits and filling in of depressions in the surface of the country.

SUMMARY OF PHYSIOGRAPHIC HISTORY

1. The Doré series, the earliest known Precambrian sediment in northeastern Ontario, was deposited as a continental formation upon a surface of rugged topography. An earlier period of mountain-building and erosion is suggested by the presence, subjacent to the Doré conglomerate, of an older granite mass, apparently of large dimensions.

2. From Doréan time until the end of Timiskaming time the region was apparently a land area of considerable, if not high relief, and the seat of prolonged volcanic activity.

3. A period of mountain-building (pre-Huronian) and complete reduction to a peneplain followed, affecting the whole region. A

[1] W. H. Collins and T. T. Quirke, *Geol. Surv., Can.*, Memoir in course of preparation.

[2] *Loc. cit.*

conception of the time involved is obtainable by comparison with the rate of formation and reduction of the Rocky, Coast, and Appalachian Mountains.

4. From the Bruce period until the Keweenawan the region was apparently a land area or one of shallow and intermittent submergence.

5. Following or during the Keweenawan another (third) process of mountain-building (Killarnean) took place which affected only the southern portion of the region. These Killarnean Mountains were reduced to a state of fairly low relief before the Ordovician marine sediments were deposited upon them.

6. From Ordovician time until the present the region has been subjected only to gentle epeirogenic oscillations and shallow submergence; its relief was low throughout this interval and it now forms a glaciated peneplain.

7. From the earliest time of which a geological record remains, the region of which northeastern Ontario is part, has behaved as a positive element of the earth's crust.

A NEW OCCURRENCE OF CRISTOBALITE IN CALIFORNIA

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Cristobalite, one of the rarer high-temperature forms of silica, was first described from the andesite of Cerro San Cristobal, near Pachuca, Mexico, by vom Rath,[1] and was established as a distinct mineral species by Mallard.[2] Artificial cristobalite has been prepared in the Geophysical Laboratory at Washington and its properties and its relation to the other forms of silica have been studied by Fenner.[3] Silica bricks are made up of artificial cristobalite and tridymite, and so these minerals are of some importance to the metallurgist.

The work of the Geophysical Laboratory is extremely valuable, but of especial interest to the mineralogist and petrographer is the actual occurrence of these minerals in nature. The laboratory production of such artificial minerals is largely to aid in the interpretation of natural occurrences. Cristobalite has been known from five or six foreign localities for some time and in 1918 the writer[4] described it from two American localities, both in California. Since that time he has obtained specimens from five additional American localities.

The cristobalite described in this paper, like the Yellowstone Park occurrence recently described,[5] is found in a rhyolitic obsidian. The exact locality of the specimens could not be ascertained. The material was placed in the writer's hands by Mr. R. M. Wilke, mineral dealer of Palo Alto, California. Mr. Wilke obtained the specimens from a prospector, who would not divulge the locality. Mr. Wilke, however, says "I am sure the place is somewhere in the

[1] *Neues Jahrb. Min.* (1887), pp. 1, 198.

[2] *Bull. Soc. Min. France,* Vol. XIII (1890), p. 172.

[3] *Amer. Jour. Sci.* (4), Vol. XXXVI (1913), pp. 331–84.

[4] *Ibid.,* XLV, pp. 222–26.

[5] *Amer. Mineralogist,* Vol. VI (1921), pp. 4–6.

northwest corner of San Bernardino County, to the northwest of Barstow, probably within 40 to 50 miles from Barstow." The geological map of California compiled by Professor James Perrin Smith and published by the California State Mining Bureau shows a number of outcrops of volcanic rocks northwest of Barstow, and so Mr. Wilke is probably correct as to the approximate locality.

THE OBSIDIAN AND ITS LITHOPHYSAE

The specimens consist of dark gray to almost black obsidian ($n = 1.483 \pm .003$) with a faint banded structure and bright vitreous luster. In thin fragments the obsidian shows on microscopic examination numerous, minute, rod-shaped crystallites arranged in parallel lines and a few microlites.

The obsidian contains many light gray spherulites which range from 5 to 25 mm. in diameter and are fairly evenly distributed, though sometimes two of them coalesce. The spherulites are more or less flattened; some of them are elongate, and most of them are somewhat irregular in outline. With a few exceptions they are hollow and hence may be called lithophysae. It is estimated that the spherulitic material occupies only about a fifth to a half of the original space. The spherulites are for the most part ruptured, and deep cracks extend almost to their margin, so that the spaces left are usually very irregular in outline. The cracks give some of the lithophysae a superficial resemblance to mud-cracks. The thickness of the spherulitic material is often only about a tenth of the radius of the original cavity.

Accompanying the obsidian specimens were a number of loose spherulites or lithophysae, which had been broken out of the obsidian. They are much more regular than the imbedded lithophysae just described. One of these is shown in the photographic enlargement (Fig. 1). They have a more or less well-defined hollow space at the center and show a slight tendency to concentric structure, as may be noticed in the photograph.

It seems probable that both the expansive force of the gas within the cavity and the tension due to cooling of the surrounding glass were responsible for the formation of the lithophysae.[1]

[1] For a discussion of the origin of lithophysae, see paper by Wright, *Bull. Geol. Soc. Am.*, Vol. XXVI (1915), pp. 255–86.

MINERALS OF THE SPHERULITES

The solid portions of the spherulites consist of two minerals, orthoclase and cristobalite, and of these orthoclase predominates. The orthoclase and cristobalite occur in fibrous aggregates, which on microscopic examination prove to be intergrowths. In spots, which are probably cross-sections, they have an intricate interlocking structure which suggests graphic texture. The orthoclase is

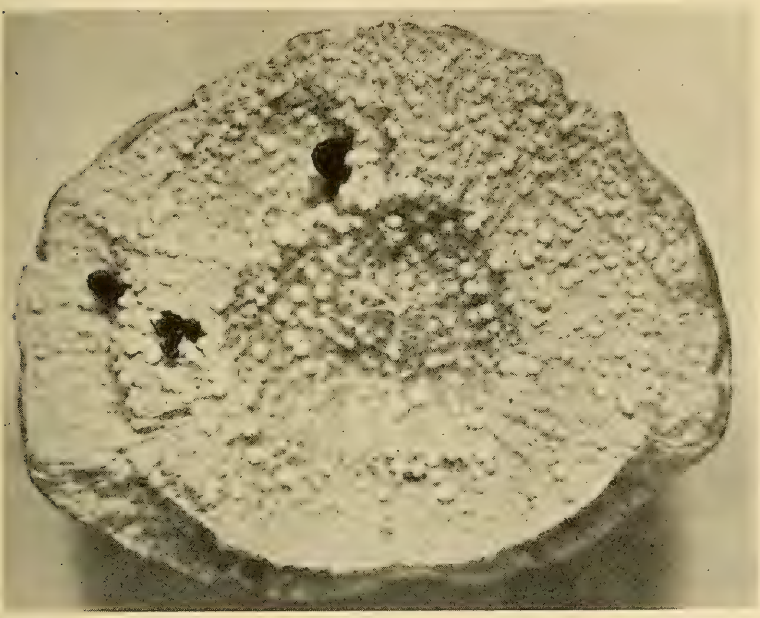

FIG. 1.—(×5) Cristobalite and Fayalite in a Lithophysa of the Obsidian from San Bernardino County, California.

cloudy, while the cristobalite is clear. The cristobalite is identified by its index of refraction, which is slightly greater than 1.480. Most of the cristobalite areas are isotropic, but occasionally they show very weak double refraction. The double refraction is uniform, which distinguishes the cristobalite from the glass which has practically the same index of refraction.

It seems probable from the descriptions in the literature that such orthoclase-cristobalite spherulites are characteristic of rhyo-

litic obsidians, but have not been recognized before on account of the difficulty of distinguishing the cristobalite. It was with great difficulty that the writer succeeded in proving that the mineral intergrown with the orthoclase was cristobalite.

Imbedded in these larger spherulites are numerous, very minute, spherical bodies, which consist largely of orthoclase with small amounts of cristobalite. These probably represent earlier formed spherulites of orthoclase which have been recrystallized during the later main period of spherulite production. Such composite spherulites have been described by Rutley[1] from another locality in California. Rutley speaks of "isotropic matter" between the rods or fibers of orthoclase, which in all probability is cristobalite.

There is a little magnetite imbedded in the spherulitic material.

MINERALS OF THE LITHOPHYSAL CAVITIES

The following minerals were identified in the lithophysae: orthoclase, cristobalite, tridymite, opal, magnetite, and fayalite. These minerals occur on the walls of the lithophysal cavities and the specimens make beautiful microscopic mounts (Fig. 1).

Orthoclase.—On the free surface of the cavities the orthoclase takes on the form of branching rods with weak birefringence and positive elongation (parallel to γ). The index of refraction is $1.517 \pm .003$.

Cristobalite.—The cristobalite occurs in minute (0.2–0.5 mm.) translucent white spherulites, which are scattered over the surface of the lithophysae as illustrated in the photograph. In fragments the cristobalite shows a well-defined spherulitic structure with elongation of the crystals parallel to the faster ray α. There is intricate polysynthetic twinning and the extinction is oblique. The double refraction is very weak.

The index of refraction of the cristobalite is $1.483 \pm .003$, which was determined by means of immersion liquids. This determination positively distinguishes it from tridymite which has indices of refraction of 1.469–1.473.

The specific gravity of the cristobalite is $2.36 \pm .04$, which was determined by means of a mixture of acetylene tetrabromid and

[1] *Quar. Jour. Geol. Soc.*, Vol. XLVI (1890), pp. 423–28.

benzol. (It sank in the liquid in which gypsum [sp. gr. = 2.32] remained suspended and floated in the liquid in which brucite [sp. gr. = 2.39] remained suspended.)

In still another respect did the mineral agree with cristobalite. It is infusible and on heating to a high temperature by means of a blowpipe it became semi-transparent and on cooling it suddenly became translucent again. This sudden change in appearance, which may serve as a blowpipe test for cristobalite, is due to the conversion of the high-temperature β-cristobalite to the low-temperature α-cristobalite, which, according to Fenner, takes place in artificial cristobalite at a temperature varying from 198 to 240° C.

Tridymite.—The exterior of most of the cristobalite spherulites when examined with a high-power binocular microscope are seen to be studded with very minute six-sided crystals of tabular habit. These are identified as tridymite by their index of refraction, $n = 1.475 \pm .005$. The tridymite is transparent in contrast to the translucent cristobalite. Some of minute cristobalite spherulites apparently are converted into tridymite, but careful microscopic examination shows that the cristobalite is simply covered with the tridymite.

Opal.—Several of the lithophysal cavities are coated with a thin layer of hyalite opal (n slightly less than 1.45), which was evidently the last mineral formed. No chalcedony or quartz could be detected in any of the specimens.

Fayalite.—A few, small (1 mm.), brown, transparent crystals of fayalite (Fe_2SiO_4) are found on the free surfaces of the lithophysae. Three crystals (dark areas) are shown in the photograph. They are tabular in habit and resemble the fayalite from the spherulitic obsidian of Yellowstone National Park. The fayalite has an index of refraction greater than 1.74 and gives an iron borax bead test. Some of the crystals have been altered to a black opaque substance.

Magnetite.—Very minute octahedral crystals of magnetite are visible with the high-power microscope.

FORMATION OF THE MINERALS

The minerals lining the walls of the lithophysae evidently were formed by hot gases liberated by the crystallization of the spheru-

lites. The orthoclase and cristobalite are largely products of recrystallization of the spherulites. The cristobalite probably was formed at a comparatively high temperature and as the temperature became lower, tridymite was formed, and at about the same time fayalite and magnetite appeared. The opal is the only mineral that was formed by ordinary solutions. The oxidation of the fayalite, a slight staining of the lithophysae, and whitening of the orthoclase rods are the result of weathering.

CRISTOBALITE IN SPHERULITIC OBSIDIAN

The Yellowstone Park occurrence, the San Bernardino County occurrence of the present paper, and two undescribed Californian occurrences, all taken together, point to the conclusion that cristobalite is one of the characteristic minerals of spherulitic obsidian. In fact it seems to be more common in such rocks than tridymite. It is probable that in some cases cristobalite has been identified incorrectly as tridymite. For example the minute pellets referred to and figured by Iddings[1] in the spherulitic obsidian of Yellowstone Park are probably cristobalite instead of tridymite.

[1] *Seventh Ann. Rept. U.S. Geol. Survey* (1888), p. 264, Pl. 12, Fig. 3.

FAULT FEATURES OF SALTON BASIN, CALIFORNIA[1]

JOHN S. BROWN
U. S. Geological Survey

OUTLINE

GENERAL FEATURES

The Salton Basin is a great natural depression in the southeastern corner of California (Pl. I). Its lowest elevation is 273.5 feet below sea-level,[2] and the lowest part of the basin is now occupied by the more or less ephemeral lake known as Salton Sea, which was created in 1905 by the accidental escape of Colorado River during the diversion of irrigating water to Imperial Valley. Physiographically, Salton Basin is continuous with the depression occupied by the Gulf of California, and the only topographic barrier that prevents the access of sea-water to the basin is a delta dam built up in recent geologic time by Colorado River. At its lowest point this dam is less than 50 feet above sea-level.

SURROUNDING MOUNTAINS

The axis of the basin trends southeast-northwest, and at its northwest extremity the basin narrows nearly to a point, being connected by San Gorgonio Pass to the Pacific Slope. Mountain ranges from 2,000 to 10,000 feet in height flank the basin on the

[1] Published by permission of the Director of the United States Geologic Survey.

[2] There is some question as to whether the exact elevation of the lowest point of the basin, now covered by Salton Sea, is −273.5 or −287 feet. See *U.S. Geol. Surv. Water-Supply Paper 213*, p. 30, for discussion and statement that former figure is probably correct.

northeast and southwest, reaching their highest elevation in the vicinity of San Gorgonio Pass, where the basin is narrowest. The mountains on the southwest are generally known as the Peninsular ranges. They extend down into Mexico, and form the crest of the peninsula of Lower California. They include the San Jacinto, Santa Rosa, Vallecito, and Laguna ranges, and their crest separates the drainage of Salton Basin from that of the Pacific Slope. The summit of the Peninsular Mountains is well watered and generally timbered. Along it there are numerous tracts of gently rolling land sculptured into only a moderate relief. Such are Pinyon Flat, Montezuma Flat, and the region near Jacumba. These tracts are doubtless remnants of the surface of the region before it was uplifted to form the present mountain chain. The eastern slope of the Peninsular ranges, however, is precipitous, and its dissection deep.

The San Bernardino Mountains and other ranges form the northeast wall of the basin. To the southeast these break up into a series of low, disconnected ranges. All of them are barren rock masses, at whose feet are gathered great débris fans.

THE BASIN FLOOR

A great part of the basin floor is a monotonous plain formed of alluvium brought in from every side. In the center the alluvium is fine silt, but at the mountain borders it is a coarse fanglomerate. Over some of the basin floor there is a considerable deposit of sand in the form of dunes. About the borders there are, at various places, exposures of soft, folded, sedimentary beds, which have been carved into picturesque badlands. Since the basin is practically rainless, vegetation is scant, and restricted to desert plants, such as creosote, cacti, ironwood, and, at places, mesquite.

One other feature of the basin floor deserves mention. Near its center, at the southeast end of Salton Sea, is a large group of active mud volcanoes, associated with small exposures of recent lava (obsidian).

STRATIGRAPHY

The rocks of Salton Basin have been studied in detail at only a few places. For the purposes of this paper, however, they fall naturally into three classes. The first class comprises pre-Tertiary

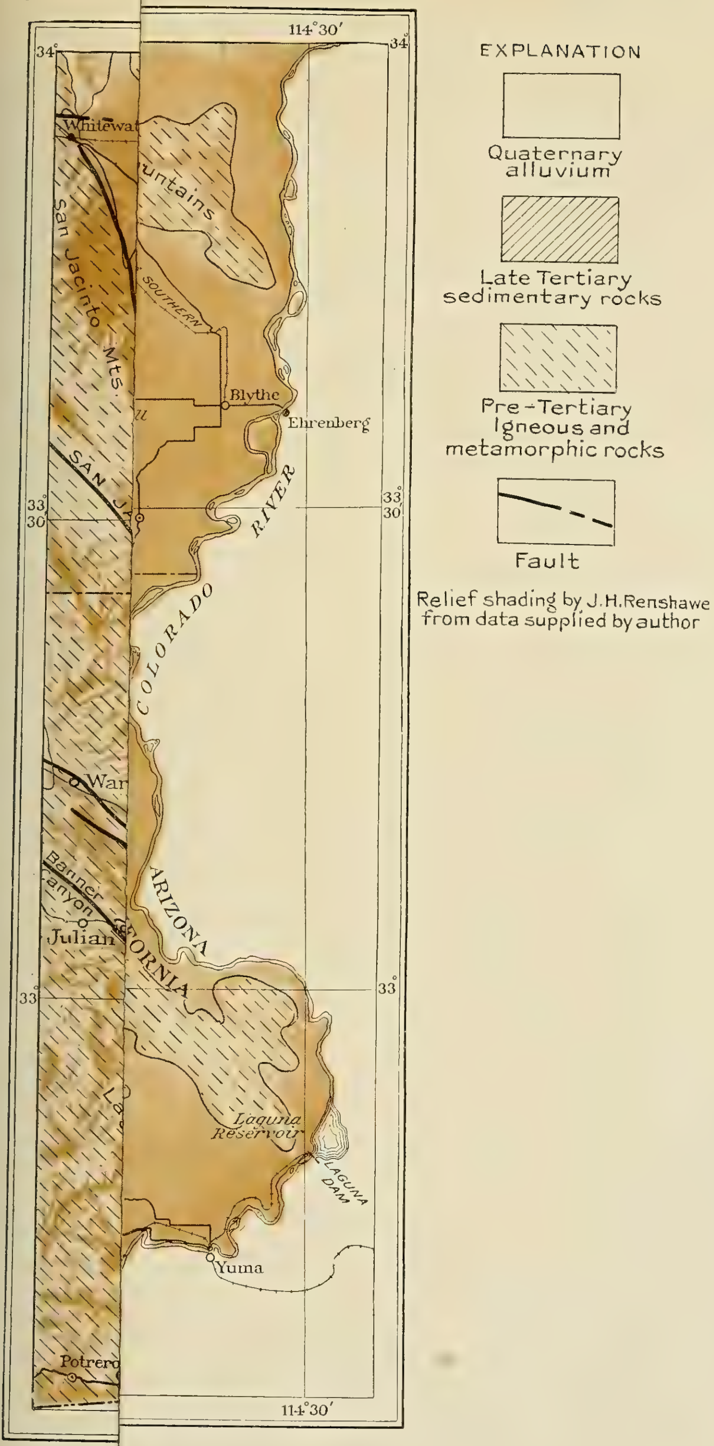
114°30′
34°
Whitewat
untains
San Jacinto Mts.
SOUTHERN
Blythe
Ehrenberg
SAN J
33°30′
RIVER
COLORADO
War
Banner Canyon
Julian
ARIZONA
ORNIA
33°
Laguna Reservoir
LAGUNA DAM
Yuma
Potrero
EXPLANATION
Quaternary alluvium
Late Tertiary sedimentary rocks
Pre-Tertiary Igneous and metamorphic rocks
Fault
Relief shading by J.H.Renshawe from data supplied by author

Plate I

Reconnaissance map of the geology and topography of Salton Basin and vicinity

crystalline rocks, and forms the basement rock of all the region. There are large bodies of schist and gneiss, and smaller amounts of marble and quartzite. The age of these metamorphics is unknown. Most of them are Paleozoic, but a part probably is pre-Cambrian. Then there are still greater masses of granite, monzonite, and diorite intruded into the metamorphic rocks. These intrusives are probably Mesozoic. The various crystalline rocks constitute the mass of all the mountain ranges.

The second division of rocks consists chiefly of sedimentary beds of late Tertiary age. The series has a total thickness of several thousand feet, and consists of sand, shale, and conglomerate, with some salt and gypsum. Generally the beds are more or less folded and broken, but they are everywhere soft and poorly consolidated. On them is developed the badland topography mentioned above. In the Carrizo Creek region these beds contain an abundant late Tertiary marine fauna. Elsewhere they are apparently unfossiliferous, and probably terrestrial in origin.

Interbedded with the Tertiary sediments at some places are beds of basaltic lava and tuff sometimes 100 to 200 feet in thickness. These volcanics constitute only a small portion of the series.

Quaternary alluvium is the last division of the rock section. It forms most of the basin floor, and fills many of the adjacent valleys. Its areal extent is greatest of the three classes.

FORMATION OF SALTON BASIN

Salton Basin has evidently existed as a marked depression since times previous to the latter part of the Tertiary period, for it has received sediment during the formation of the last two rock series. Neither the Quaternary nor the Tertiary sediments are displaced by any such vertical movements as must have occurred during the formation of the basin. The Tertiary beds are seldom found at elevations above 1,000 feet, and the Quaternary shows but few recognizable displacements and these are of small size.

It has been tacitly assumed by geologists that the basin originated as a dropped fault block, or graben. This hypothesis, suggested by the topographic features, is greatly strengthened by the fact that the basin lies directly on the course of the San Andreas

rift, a notable fault along which occurred the displacement that caused the San Francisco earthquake of 1906. The California Earthquake Commission traced this fault continuously from San Francisco southeastward to the very tip of Salton Basin. In its report[1] the commission suggests that the rift probably continues southeast, and is connected in some way with the formation of the basin. In the Peninsular Mountains, southwest of the basin, there are also several well-recognized faults, portions of which have been mapped, but these have generally not been traced eastward to their visible terminations. These faults and their relation to the faults described here are shown in Figure 1.

The evidence of faulting in this region is as a rule, derived from the topography, and can only rarely be established by stratigraphic criteria. Igneous and metamorphic rocks, such as compose the mass of the mountain ranges, are so homogeneous in nature that it is often impossible to determine differences in the rocks exposed on either side of a fault, while the Quaternary material which fills most of the valleys has been deposited since the faulting occurred and obscures it in many places.

THE INDIO FAULT

At the base of the crystalline ranges (Little San Bernardino, Orocopia, etc.) bordering the upper part of the northeast side of the basin, lies a conspicuous chain of low, badland hills in which are exposed the late Tertiary sedimentary beds, and occasionally small patches of the underlying bedrock. This chain of hills is separated by a slight break into two ranges known as the Indio Hills and Mecca Hills. The Indio Hills have a total length of 20 miles, and a width of 2 or 3 miles. The Mecca Hills are also about 20 miles long, and at some places are 4 or 5 miles wide. The general slope of the hills is southwest, where they dip beneath the basin floor. They are separated from the crystalline ranges northeast by a trough from 1 to 3 miles in width filled with coarse alluvial débris. At some places the canyons that head in the main mountains cut entirely across the hills, as at Shaver Canyon and the Thousand

[1] *California Earthquake Commission Report*, Carnegie Inst. of Wash., 1910.

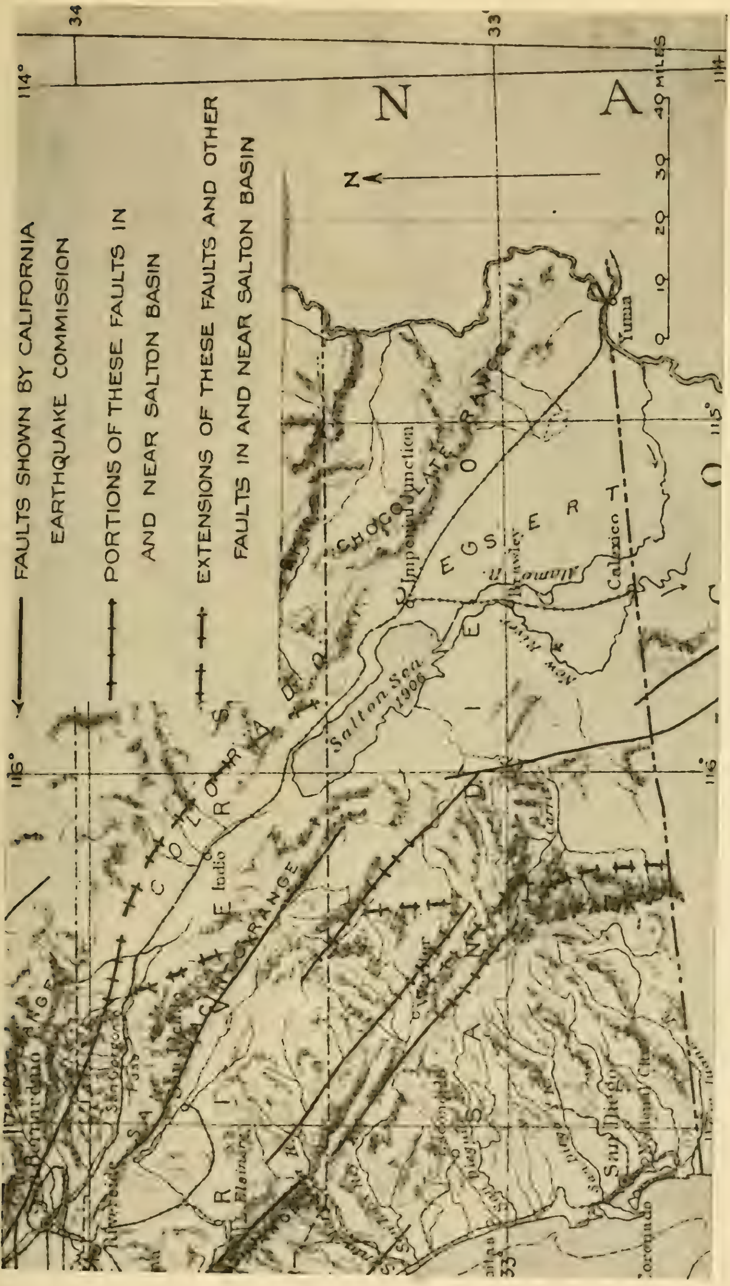

FIG. 1.—Prominent faults of Southern California. (After California Earthquake Commission)

Palms. At other places they are deflected by the foothills into long, longitudinal valleys between the crystalline and Tertiary rocks.

The Indio and Mecca Hills have undoubtedly been lifted from the basin floor by a fault for which the name of Indio fault is suggested. This fault passes along the northeast border of the hills formed by the Tertiary rocks. Near Indio there is for several miles a steep and very perfect scarp, generally not more than 100 to 300 feet in height. The broken Tertiary beds dip southwest from the present face of this escarpment at angles of about 45°. Along the northeast side of the Mecca Hills the scarp is less perfect, but still constitutes a very well-defined ridge. West of Dos Palmas it is a low bluff along the east base of a point of clay hills.

Although the Indio fault as here described was observed only at a few scattered points, it appears reasonably certain that it extends throughout the length of the Indio and Mecca hills. The most critical point at which it should be examined is the contact with the crystalline bedrock in the Orocopia Mountains, where there appears to be no marked separation of the crystalline range from the bordering sedimentary foothills. The fault doubtless continues at least as far south as an isolated hill of Tertiary material near Durmid, which has probably been elevated in the same manner as the hills farther north. Its total length, then, is about 50 miles, and its form an arc of gentle curvature. Its northwestern end has a trend nearly west, and lies in the direct line of probable extension of the San Andreas rift, from which the actual separation is only a few miles in length. The conclusion seems justified that the Indio fault represents the extension of the San Andreas rift. At the southeastern end the fault-trend is more nearly south, and points suggestively toward the mud volcanoes.

It should be noted that the throw of this fault is opposite to that of the San Andreas rift farther northwest, and also to the original displacement which must have formed the Salton Basin. Such reversals of throw along prominent fault lines are, however, neither impossible nor uncommon,[1] and occur at several places along the course of San Andreas rift farther northwest.

[1] The Bright-Angel fault in the Grand Canyon is a case in point. *Science*, April 24, 1908, p. 667.

FAULTS SOUTHWEST OF SALTON BASIN

The faulting along the southwestern side of the basin is apparently of two ages, and took place in somewhat different directions, the intersection of the two fault systems probably accounting for the present irregular outline of the basin. Thus great mountain salients, such as the Santa Rosa Mountains, the Vallecito-Fish mountain spur, and the projection of the Peninsular Mountains along the Mexican Boundary, are separated by big re-entrant valleys, such as San Felipe Valley and the Carrizo Creek Valley.

The oldest of these fault systems, if this inference is correct, has a strike about N. 10 W. and is represented by three notable escarpments. One lies along the east base of the San Jacinto Mountains, passing up Palm Canyon. Another is at the west side of Borego Valley. The third extends from Agua Caliente Springs southward up Carrizo Gorge, along the east face of the Laguna Mountains.

Evidence of a fault along the northeast and east face of Mount San Jacinto was obtained near Whitewater. Just west of Whitewater Point the mountain face is composed of pink and gray granite, and of a grayish marble. The marble and granite are arranged in layers turned on edge with a strike about N. 20 W., and a dip of 75° or more to the northeast. Although the quantity of marble is much less than that of the granite it constitutes a considerable part of the mountain mass, the layers ranging from a few inches to 50 feet in thickness. The alternation of rocks is well exhibited in a prospect tunnel in Sec. 23, T. 3 S., R. 3 E., where the material penetrated has the appearance of a gigantic fault breccia, and the contact surfaces are abundantly slickensided. This intermixture of material probably resulted from step-faulting, the successive breaks along many parallel lines causing an intimate mixture of the different rocks. Associated with this prominent fault line is the warm spring at Palm Springs, whose water is believed to be derived from granitic rocks[1].

West of Borego Valley no observations were made to confirm the existence of a fault except to note that the mountain front in that region is a very steep and straight escarpment from 2,000 to 4,000 feet in height.

[1] The inference is based on unpublished analytical data.

The southernmost fault scarp of this series was observed in Canebrake Canyon, and at Agua Caliente Springs. At both places the mountain front for several hundred feet from the lowland border consists of rotten, grayish granite, broken into minute joint blocks, kaolinized, and altered. Farther in the interior of the mountains the rock is dense and unweathered. There is much evidence of hydrothermal alteration, a very natural thing to expect, at Agua Caliente Springs, where a large number of springs, part of which yield warm water, issue from the granitic rocks.

Cutting across this first system of faults is a system which strikes approximately N. 45 W., and which is represented by several prominent faults. The most northerly fault of this system is the San Jacinto fault, which passes south and west of San Jacinto Mountains, extending through Hemet Valley and down Coyote Canyon. For several miles it traverses the northeast side of Borego Valley.[1] The uplift along this fault was on the northeast. Coyote Mountain on the northeast of Borego Valley is part of a prominent spur elevated in this uplift, and is bordered on the southwest by well-defined scarp, which displaces Tertiary beds. It is probable that the San Jacinto fault extends at least as far as Borego Mountain, but it is much obscured in that direction by recent alluvial deposists. Movement occurred along this fault at the time of the San Jacinto earthquake of 1899.

Several faults which have been recognized in the vicinity of Warner Valley[2] extend southeastward into the western part of this region. One of these which passes nearly through Warner Hot Springs traverses Grapevine Canyon, turns nearly east along a part of San Felipe Creek, and disappears near The Narrows. Its uplift was on the northeast, and the tongue of granitic rock south of Borego Valley and in the vicinity of The Narrows is believed to have originated from the uplift. A fault extends from Warner Valley down the headwaters of San Felipe Creek, and its eroded scarp forms the northeast side of San Felipe Valley, being a promi-

[1] H. W. Fairbanks, *California Earthquake Commission Report*, Carnegie Inst. of Wash., 1910, p. 47.

[2] A. J. Ellis, and C. H. Lee, "Geology and Ground Waters of the Western Part of San Diego County, Cal.," *U.S. Geol. Surv. Water-Supply Paper 446*.

nent mountain wall for 12 or 15 miles. Another fault passes through Banner Canyon and Rodriguez Canyon, and extends along the north side of Mason Valley and Vallecito Valley, the mountain walls of these valleys probably representing considerably eroded fault scarps. The last two faults unite in the vicinity of Agua Caliente Springs, and are not known to continue farther, but may extend along the north side of Carrizo Valley at the base of Vallecito Mountains and Fish Mountains.

VALLEYS FORMED BY FAULTING

Associated with the second system of faults are several peculiar valleys for whose formation the faults have been responsible. The largest of these valleys are Borego Valley, San Felipe Valley, Mason Valley, and Vallecito Valley. Collins Valley, adjacent to Borego Valley, and a little valley less than a mile in extent at Banner, were formed in the same way. All of these valleys have for their northeast boundary a high, steep mountain wall which originated as a fault scarp along some one of the faults mentioned above. Thus Borego Valley and Collins Valley lie southwest of the San Jacinto fault. The general shape of each valley is triangular, and the south and west sides are much more irregular in outline than the northeast side, the mountainous borders on these sides being also somewhat less abrupt than those on the northeast. Most of the valleys are high at the southwest, and the drainage is to the northeast. This has probably been the natural result of the tilting of the faulted strips, which have all been dropped down on the northeast and elevated on the southwest.

Most of the faults have forced the drainage to follow northwest-southeast directions, particularly in the various canyons such as Coyote Canyon, Grapevine Canyon, and Banner Canyon, but some streams, such as San Felipe Creek, northeast of San Felipe Valley, and Banner Creek at Banner, occupy deep gorges which cut directly across the fault scarps at the northeast border of these valleys. It is probable that these streams existed before the faulting, and that the faulting took place gradually, the streams cutting down as fast as the rocks were lifted across their beds. A further suggestion that the earlier drainage lines may have had a northeast trend is

afforded by the granite ridges which divide some of the valleys. San Felipe Valley, for instance, is cut nearly in two by a low spur of granitic rock projecting from the southwest, while Mason Valley and Vallecito Valley are entirely separated by such a ridge, except for a very narrow, rock-cut canyon. These ridges may very likely represent drainage divides which existed before the faulting.

TYPE OF FAULTING

Most of the faulting observed is of the normal type. The Indio fault is associated with much folding, and it is possible that it may be in part due to thrust movements.

AGE OF FAULTING

The age of the various faults is very difficult to establish, since the age of the rocks displaced is so indefinitely known. The original settling of the Salton Basin must be pre-late Tertiary in age, because in the resulting basin great thicknesses of late Tertiary sediments were deposited. Considerable faulting has occurred since the deposition of these beds, such as that along the Indio fault, and the San Jacinto fault where Tertiary beds are displaced. The fact that movement has occurred along the recognized fault lines during recent notable earthquakes in California indicates that some of those faults are still active; and the excellent state of preservation of many of the scarps suggests that much of the displacement along some of them has occurred in Quaternary time.

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MARINE UPPER CRETACEOUS AND A NEW ECHINOCORYS FROM THE ALTAPLANICIE OF BOLIVIA[1]

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It is not surprising that rocks of Upper Cretaceous age should be present on the high plateau of Bolivia since the gypsiferous shallow water phase of the Upper Cretaceous which represents the several typically developed marine horizons that are so abundantly represented in the more northern parts of the Andean geosyncline (e.g., in central Peru), is conspicuous in the Eastern Andes of Bolivia and furnished the writer with marine fossils at two localities in the Department of Potosí.

It may be true also that these marginal Upper Cretaceous deposits of Bolivia, which are essentially reddish sandstones and gypsiferous shales, with subordinate beds of limestone, are present in considerable amount beneath the late Tertiary and more recent deposits that make up most of the surface of the high plateau except where older rocks are folded and project through these thick, surficial deposits.

No Cretaceous rocks have heretofore been known from the Altaplanicie, however, although it is true that Steinmann called the rocks at Corocoro Cretaceous. This was based solely on the fact that the Corocoro rocks were red, and as the red rocks near Potosí, 375 km. distant, were known to be Cretaceous, the unwarranted assumption was made that the Corocoro rocks also were Cretaceous. Many have followed Steinmann's opinion, as, for example Douglas in his recent geological sections across the Andes,[2] although it would seem that if color is to be an age criterion, an Englishman would consider red as indicative of Old Red or New Red age, as did Forbes in his classic studies of Bolivian Geology.

[1] *George Huntington Williams Memorial Publication No. 9.*

[2] J. A. Douglas, *Quart. Jour. Geol. Soc. Lond.*, Vol. LXXVII (1914), pp. 1–53; Vol. LXX (1920), pp. 1–61; Vol. LXXVII (1921), pp. 246–84.

As a matter of fact the writer showed in 1917 that the Corocoro rocks were of Pliocene age[1] and this age determination is fully and completely established by detailed field studies made by Singewald and Berry in 1919, the results of which are now awaiting publication.[2]

The presence of true Upper Cretaceous in this region rests on the species of Echinocorys or Ananychites described below (Figs. 1–3), for which I am indebted to Señor Arturo Poznansky, of La Paz. It is said to have been collected at Peñas, which is just east of the southern end of Lake Titicaca in the Department of La Paz, and 55 km. northwest of the city of that name. It was not possible for me to visit the locality, but there is no reason for doubting its correctness since the specimen was newly collected at the time of my visit to La Paz and must have come from the near vicinity of the place named.

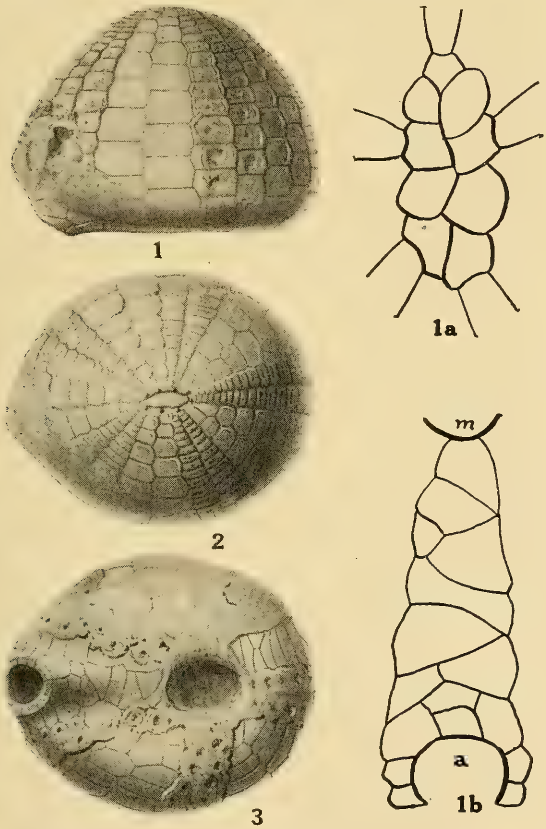
The specimen in itself is of great interest since it is, to the best of my knowledge, the first specimen of this interesting genus, so excessively abundant in the Upper Cretaceous of Europe, to be recorded from South America, and the third or fourth to be recorded from the Western Hemisphere. It does not agree with any of the numerous described species and may be called in honor of its progressive collector *Echinocorys* (*Ananychites*) *poznanskii* sp. nov.

It may be described as follows: Ambital outline elliptical, rounded in front and somewhat narrowed behind. Profile (i.e., transverse section) subcircular, the apex broadly rounded. Peristome elliptical 7 mm. in length by 10 mm. in width, situated about two-fifths back from the anterior margin, hence relatively larger and slightly more posterior in position than is commonly the case in this genus. Periproct posterior, subambital in position, large, elliptical in form, with a length of 8 mm. and a width of 6 mm. The apical system is largely obscured by calcitic incrustations. As near as it can be made out it consists of four larger genitals and five smaller oculars arranged as indicated in the accompanying sketch (Fig. 1*a*). The plastron appears to have been smooth and to comprise the sixteen plates shown in the accompanying sketch (Fig. 1*b*), and is unusual,

[1] E. W. Berry, *U.S. Nat. Mus. Proc.*, Vol. LIV (1917), pp. 103–64.

[2] Singewald and Berry, *Bull. Geol. Soc. Am.*, Vol. XXXII (1921), p. 66 (abstract).

if my interpretation is correct, in having a posterior pair of plates occluded, as indicated. Centrally the plastron becomes increasingly convex toward the periproct in which region it projects about 3 mm. below the oral plane of the test. The abulacral plates number



FIGS. 1–3.—*Echinocorys* (*Ananychites*) *poznanskii* sp. nov. 1, lateral view; 1*a*, sketch of arrangement of apical system; 1*b*, sketch of plastron, comprising sixteen plates; 2, dorsal view; 3, ventral view.

eighteen or nineteen normal pairs from the apex to the ambitus, very small at first and increasing regularly and rapidly in size downward. The pores are very much obscured by incrustation, the pore pairs being clearly seen only toward the equatorial region, where they are large and central in position, that is, some distance

within the outer margins of the ambulacrals. The inter-abulacrals are larger and there are ten normal pairs between the apex and the ambitus. Length of the type 5.1 cm.; width 4.25 cm.; height 3.95 cm.

These interesting and characteristic echinoids were figured as early as 1565 and are a striking element in the later Upper Cretaceous faunas of Europe. They appear somewhat abruptly in the Turonian, undergo but slight diversification in the Santonian, and become exceedingly abundant and diversified in the Campanian. They have dwindled to two known forms in the Maestrichtian and have a single Danian and a single Eocene survivor. They evidently found their optimum environment in the relatively clear and shallow waters in which the chalk was deposited, which may account for their singular rarity in the North American Upper Cretaceous where such a large proportion of the sediments are muddy, thus offering obstacles to both migration and colonization. In keeping with this theory there is a single small species known from the Vincentown lime sands of the Rancocas formation of New Jersey, *Ananchytes ovalis* Clark[1], and a second large species, *Ananychites texana* Cragin[2], from the Austin and Annona chalk in Texas and Arkansas. Both are exceedingly rare and, so far as I know, are represented by only the type specimens. The Rancocas formation was considered to be of Danian age by Clark[3] although it is probably Maestrichtian, and the Austin chalk should probably be correlated with the Santonian or Campanian substages of Europe. A single additional record of the genus in North America is an incidental and queried reference by Aquilera[4] to the presence of *Ananchytes sulcatus* Goldfuss in the Upper Cretaceous of Mexico.

Lambert's excellent monograph[5] of the genus renders comparisons easy and this new Bolivian species is seen to somewhat resemble

[1] W. B. Clark, *U.S. Geol. Survey Bull. 97* (1893), p. 74, Pl. XXXVI, Fig. 1 *a–h*.

[2] F. W. Cragin, *Fourth Ann. Rept. Geol. Surv. Texas* (1893), p. 145, Pl. XXV, Fig. 12; Pl. XXVI, Figs. 1, 2.

[3] W. B. Clark, *Geol. Soc. Am. Bull.*, Vol. VIII (1897), pp. 315–58.

[4] J. G. Aquilera and E. Ordoñez, *Datos para la geologio de México* (1893), p. 27.

[5] J. Lambert, "Étude monographique sur le Genre Echinocorys," *Mem. Mus. Roy. d. Hist. Nat. Bèlge*, Tome 2 (1903).

the European Danian species, *E. sulcatus* Goldfuss, but it appears to be most similar to the European Campanian and Maestrichtian forms, *E. Cotteaui* and *E. Duponti*, described by Lambert, who prefers to use the generic term *Echinocorys* proposed in pre-Linnean time (1732) by Breynius, and re-adopted in 1778 by Leske, rather than *Ananchites* Lamarck (1801) which has been adopted in recent American texts. The age of the Bolivian deposit would appear to be Campanian, although more definite confirmation is desirable before this correlation can be accepted as final.

FORMER COURSES OF THE ANDROSCOGGIN RIVER

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INTRODUCTION

The Androscoggin River is one of the most interesting of the many examples of disarranged drainage in New England and merits more attention than it has hitherto received.

The present study has involved a critical examination of the topographic relations of the Androscoggin and several adjacent rivers, differentiating the topography controlled by underlying bed-rock formations from the topography of surficial deposits.

Nearly all that part of the problem south and east of Berlin, New Hampshire, is covered by the topographic sheets of the United States Geological Survey; but the region north of Berlin is best shown on Hitchcock's map of New Hampshire;[2] and, finally, the hydrography of the entire area included in this investigation is shown in outline on the accompanying drainage map (Fig. 1).

TOPOGRAPHY

The drainage basin of the Androscoggin River, approximately 125 miles long in a northwest-southeast direction and 30 to 40 miles in normal breadth, may be divided into five topographic provinces, as follows: headwater, upper, middle, lower, and coastal; and in each province the river has characteristics peculiar to that province.

The Androscoggin River is formed by the junction of the Magalloway River and the drainage of the Rangeley Lakes, near Errol, New Hampshire. The headwater province extends north and east from this point to the ultimate sources of the river and will not be further considered in this paper.

[1] The writer wishes especially to express his indebtedness to President W. W. Atwood, under whose direction this work was done.

[2] C. H. Hitchcock, atlas accompanying the *Report on the Geology of New Hampshire*. New York, 1878.

The upper province includes the region between Errol and Berlin. It is bounded on the southeast by the Mahoosuc Range,[1] the

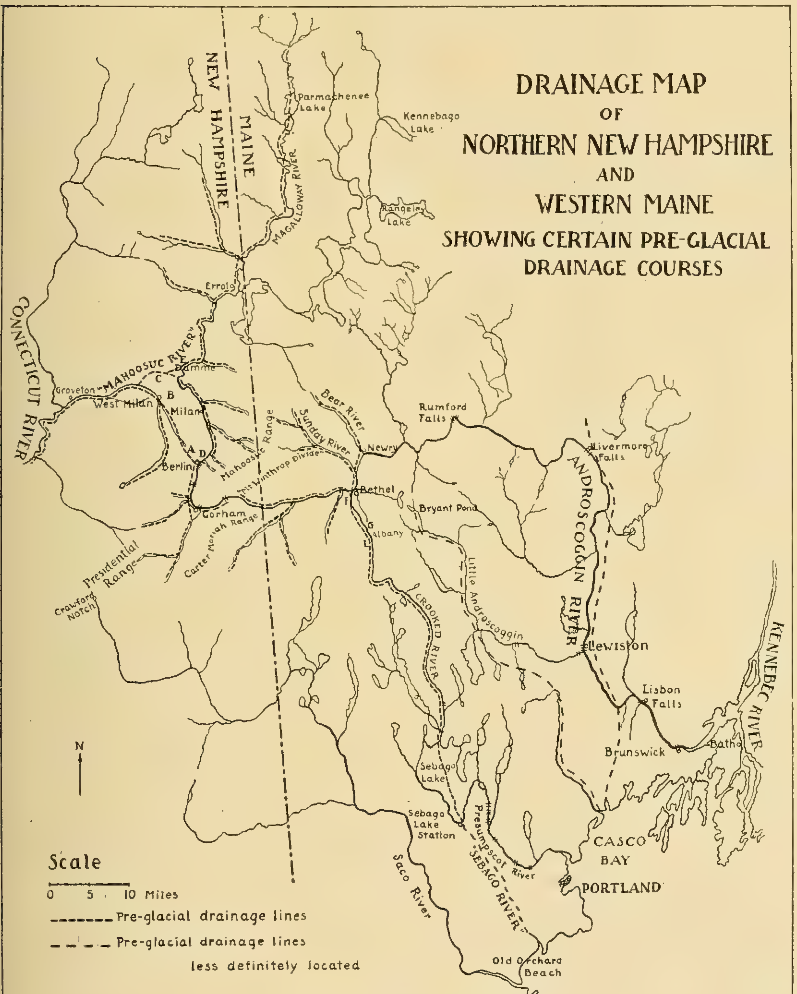

FIG. 1.—Drainage Map

northeastern extension of the White Mountains, and is characterized by broad valleys and mountains of moderate elevation. Slaty

[1] The range, extending from Gorham, New Hampshire, to Grafton Notch, Maine, and including the following mountains: Baldcap (3,100), Ingalls (3,570), Goose Eye (3,854), and Speckled (4,250), has recently been named the Mahoosuc Range.

rocks prevail in the northern part and granitic rocks in the southern part. The country is heavily mantled with glacial drift; but the existing bed-rock contours indicate that the preglacial topography was in the mature stage of dissection. The river flows southerly through this province, in a broad valley, descending 180 feet in 30 miles, or 6 feet to the mile.

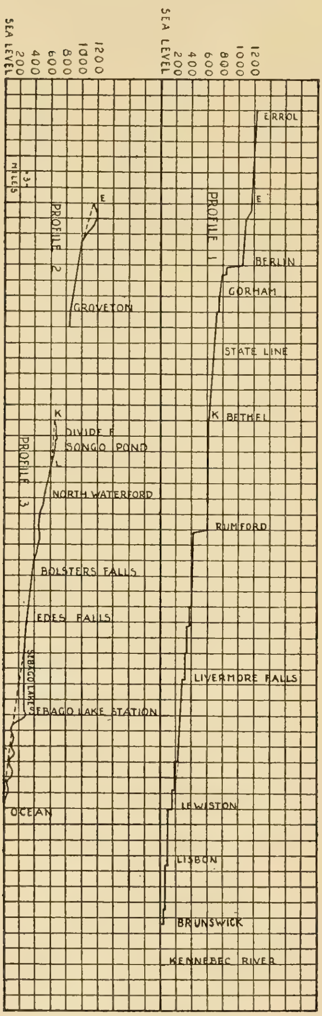

FIG. 2.—Profiles of the present and former courses of the Androscoggin Drainage

The middle province extends from Berlin, New Hampshire, on the west side of the main ranges of the White Mountains, to Bethel, Maine, on the east side, its high mountains and deep valleys contrasting strongly with the lower mountains and broad valleys of the upper province. The Androscoggin flows southerly from Berlin to Gorham through a narrow valley in granitic rocks, and then turns abruptly to the east and passes, in a deep valley, through high mountains of massive siliceous schists. These schists, the most resistant rocks of the region, form the main ranges of the White Mountains, and extend northeasterly into Maine.

In the middle province the river descends 420 feet in 30 miles or 14 feet to the mile, thus having a gradient two and one-third times as great as in the upper province. At Berlin the river drops 200 feet in several falls; and there are a number of other falls and rapids in the first ten miles below that city. Profile 1 (Fig. 2) shows the distribution of fall on the river and emphasizes the contrast of the river gradients above and below Berlin.

Comparison of the middle and upper provinces shows that in the former the valley is younger and deeper, suggesting a great change in the history of the river. These facts, together with the peculiar behavior of the river at the great bend near Gorham, where the river turns abruptly from less resistant rocks into high mountains of more resistant rocks, lead to the belief that the upper part of the valley has been occupied much longer by the river and that it formerly had another route to the sea.

The lower province, extending from Bethel to tidewater at Brunswick, is marked by broad valleys, low passes, and low, rounded mountains. As the sea is approached the mountains disappear and the hills are very low, with the exception of a few monadnocks. The preglacial topography of the region near the mountains was in late maturity and near the coast it was in old age.

In the lower province the course of the river differs greatly from its course in the other provinces in being very irregular, with many sharp turns, as can be seen on the drainage map (Fig. 1) or on the topographic sheets. In this province the river descends 635 feet in 98 miles or 6.5 feet per mile; but this descent consists of a number of falls with quiet stretches between. The numerous sharp turns, narrows and falls indicate that the present course of the river is not normal, and lead one to look for a more direct route.

The coastal province extends from the head of tidewater to the open ocean and is characterized by drowned valleys and by islands. In this province, about 8 miles below Brunswick, the Androscoggin joins the Kennebec, with a retrograde course, that is, the direction of the tributary is reversed in relation to the main stream, the apex of the acute angle between the two streams pointing up the main stream. This abnormal junction of the two rivers is good evidence that the Androscoggin is not here flowing in a normal course.

The higher ranges of the White Mountain system have a northeast-southwest trend; but seaward from these ranges the ridges have a north-south or northwest-southeast direction. This general trend of the topography seaward from the mountains is well shown by the numerous north-south elongated lakes, valleys, and ridges, and the absence of similar features with an east-west trend. There-

fore the northerly-southerly direction may be considered as normal for a valley in the region between the mountains and the sea; and the few cases of west to east courses are exceptional.

The writer believes that the present route of the Androscoggin through the mountains in the middle province is not the original course of the drainage of the watershed above Gorham, and also that the route of the river below Bethel is entirely postglacial, the present stream occupying parts of several preglacial drainage systems.

The ice sheet crossed this region in a southeasterly direction, widening the valleys and passes, and developing the characteristic U-profile.

In the mountains till is widespread, but well-defined moraines and drumlins are few. The valleys are relatively narrow, the divides are generally high, and streams are principally controlled by the bed-rock topography and not by glacial deposits.

In the lower province, just east of Bethel, the valleys are broader, the divides lower; and the streams are partly controlled by glacial deposits, while nearer the coast moraines and drumlins are common, rock hills are scarce, and stream control is largely by surficial deposits.

FORMER COURSE OF THE UPPER ANDROSCOGGIN

The present divide between the drainage to Long Island Sound and to the Gulf of Maine extends northerly from the Presidential Range between the valleys of the Connecticut and Androscoggin rivers. This divide has several low passes, one between Berlin and Groveton having a summit less than 100 feet above the Androscoggin River or 1,100 feet above sea-level. The mountains forming the divide are composed of granitic rocks and are less high and rugged than the schist mountains of the main ranges. The irregular northerly-southerly trend of the divide, and its broken character, contrast strongly with the Presidential, Carter-Moriah, and Mahoosuc ranges, which have a regular northeast-southwest trend and have only one low place, the valley of the Androscoggin at Gorham.

These facts coupled with the character of the Androscoggin valley near Gorham indicate strongly that formerly the divide was along the Carter-Moriah and Mahoosuc ranges. If this were the case, the upper Androscoggin had another outlet and the only possible alternate course would have been through the valley now occupied by the Upper Ammonoosuc to the valley of the Connecticut at Groveton.

The broad valley of the Upper Ammonoosuc extends eastward from the Connecticut and connects with the valley of the Androscoggin by three broad, low passes.

The most southerly of these passes (*A* on Fig. 3), between Berlin and West Milan, is traversed by the Grand Trunk Railway and its summit is less than 100 feet above the Androscoggin at Berlin. Dead River, a small, sluggish stream, heads in this pass and joins the Upper Ammonoosuc at West Milan. Dead River appears to have been beheaded near Berlin and before that accident it was undoubtedly large enough to make the broad valley which it now occupies.

The next pass to the north (*B* on Fig. 3) lies between West Milan and Dummer. It is broad, with a summit approximately 100 feet above the Androscoggin. No bed rock is visible in the saddle or on its slopes, and it has every appearance of being deeply drift-filled.

The third pass (*C* on Fig. 3) is about three miles farther north, where a broad branch valley connects with the Androscoggin valley by a pass approximately 100 feet above that river. This pass is very broad with gentle slopes, and no bed rock is visible.

The broad valley between Groveton and West Milan is occupied by the Upper Ammonoosuc River. The narrowest part of this valley is 6 miles west of West Milan, but it is probable that a lake a few miles to the north marks the preglacial course of the river.

The valley of the Upper Ammonoosuc was deeply filled by glacial deposits, which have been only partially cleared out by the present stream; and it is obvious that the preglacial valley was much too wide to be accounted for by the erosive action of the present river. The branch valley toward pass *C* is floored with

stratified drift. If all this drift were removed from these valleys, there would be a broad valley, ample for a large river, connecting the Androscoggin with the Connecticut.

Northeast of Berlin is a nearly level plain, rising gradually to the southeast and ending abruptly against the Mahoosuc Range.

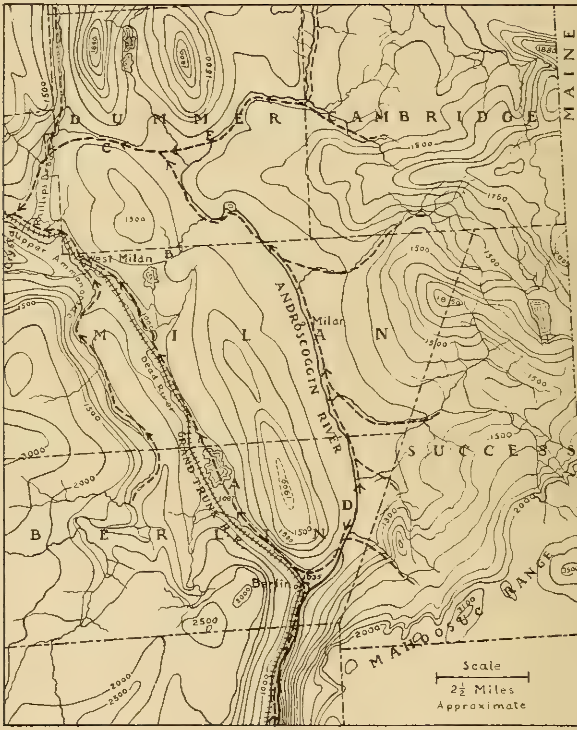

FIG. 3.—Map showing present and former drainage lines about Berlin, Dummer, and Milan, New Hampshire.

----- Former Drainage Lines

Several streams flow northwesterly across this plain and enter the Androscoggin with retrograde courses. The descent from the plain to the Androscoggin at Berlin is abrupt, indicating that the river has been rejuvenated enabling it to lower its bed faster than is possible with the smaller streams.

There are remnants of a bed-rock bench at an elevation of approximately 1,200 feet on the valley sides south of Berlin. At Gorham the elevation of the bench remnants is 1,300 feet (*1* in Fig. 4),[1] and two miles to the east their elevation is 1,400 feet (*2* in Fig. 4). The summit of Mount Winthrop (*3* in Fig. 4), a long spur projecting into the valley five miles east of Gorham, has an elevation of 1,575 feet.

FIG. 4.—View eastward from Pine Mountain, Gorham, New Hampshire

Looking eastward from Mount Winthrop, long, even-crested ridges extend into the valley; and two with elevations of about 1,100 feet appear completely to block the valley. These are evidently remnants of the floor of a valley which descended to the east from a divide where Mount Winthrop now is.

The series of bench remnants rising to the east from Berlin and culminating at Mount Winthrop mark the level of an old valley which extended from the valley now occupied by the Upper Ammonoosuc to a low pass at Mount Winthrop.

Observations from Mount Winthrop give indication of an old land surface descending on either side. On the opposite side of the present valley are benches which correspond to Mount Winthrop

[1] From a photograph by the Shorey Studio, Gorham, New Hampshire.

and represent the opposite spur of the old divide. There appears to be ample field evidence to prove that eastward from Mount Winthrop Divide the drainage was into the Gulf of Maine, and that westward it flowed to the Connecticut.

This divide prevented the Androscoggin from flowing to the east, as it now does, and the broad valley of the Upper Ammonoosuc represents its course when tributary to the Connecticut.

Of the three passes connecting the Upper Ammonoosuc and Androscoggin valleys, either *B* or *C* offers a direct route without sharp angles or reversals of direction. Pass *A* would necessitate a much longer course with a sharp turn at Berlin, and it will not be considered as the former route of the river.

A river appears, therefore, to have flowed through the present Androscoggin valley to Dummer, through pass *C* or *B*, thence down the valley now occupied by the Upper Ammonoosuc, into the Connecticut. The name "Mahoosuc River" is suggested for this stream.

Profile 2 (Fig. 2) shows the grade of this course, the full line representing the present surface and the broken line the probable bed-rock surface; and profile 1 (Fig. 2) shows the grade of the present river. A comparison of these two profiles shows that the former route has a fairly constant grade, a normal condition for a large river, while the present course drops several hundred feet in a series of falls and is characteristic of a younger river which has not yet eroded its valley to grade.

During the existence of the Mahoosuc River a stream from Mount Winthrop Divide joined a stream from Mount Washington and flowed north to the point where Berlin now stands, and then through pass A into the Mahoosuc River. Three miles north of Berlin was a low divide (*D* on Fig. 3) between the drainage to pass A and a stream which joined the Mahoosuc River at Dummer. Between divide *D* and Dummer all tributaries joined the present river with retrograde courses; and at the time when the stream in that valley flowed north instead of south, as at present, these tributaries had normal junctions with the main stream. The old drainage is shown in Figures 1 and 3.

In explanation of the existing drainage it may be stated that the modern valley of the Androscoggin below Berlin represents more erosion than could have occurred since the last ice retreat. Undoubtedly this valley was greatly widened, straightened, and deepened by the movement of ice through it, and possibly the Mount Winthrop Divide may have been removed and the present drainage brought about by ice action. But river piracy also offers a simple explanation.

The stream on the east side of Mount Winthrop Divide had a much steeper grade and thus far greater erosive power. Bethel, $17\frac{1}{2}$ miles east of the divide, has an elevation of 635 feet, and the elevation of West Milan, 23 miles west of the divide, is 1,015 feet. The descent eastward from Mount Winthrop is 57 feet to the mile, while the westward descent is 24 feet to the mile. Allowance for erosion does not materially alter the relations.

From the divide to the Gulf of Maine by the preglacial course of the lower Androscoggin is 90 miles and from the divide to Long Island Sound by the Upper Ammonoosuc and Connecticut rivers is approximately 300 miles. These facts show that favorable conditions for piracy existed.

The Androscoggin River wore its valley back through the low Mount Winthrop Divide, captured the Peabody River, beheaded the Dead River at Berlin, wore through the low divide at *D*, captured several streams from the Mahoosuc Range, finally captured the Mahoosuc River, and thus started the present drainage system.

FORMER COURSE OF THE LOWER ANDROSCOGGIN RIVER

It has been pointed out that the present course of the Androscoggin, in the lower province, between Bethel and the ocean, is abnormal and is of postglacial origin.

For the preglacial course two possible routes are to be considered: eastward along the line of the Grand Trunk Railway or southward via the valley of Crooked River. The latter appears to be the more probable route on account of its lower summit and freedom from obstructions.

The Grand Trunk Railway occupies a pass in the hills near Bryant Pond with a summit elevation of 720 feet above the sea or 85 feet above the Androscoggin at Bethel. From Bryant Pond the Little Androscoggin River flows southeasterly and joins the Androscoggin at Lewiston with a retrograde course. At Snows Falls in the town of Paris the valley is blocked by a rock hill and the stream is crowded into a very narrow gorge. The height of the pass and the obstruction at Snows Falls make it appear that this is not the preglacial course of the Androscoggin. However, glacial outwash material in the valley and pass indicate that in glacial times a large stream flowed this way.

The postglacial origin of the lower part of the Little Androscoggin is shown by its retrograde course and its interruption by two falls. The preglacial course was probably through Poland into Casco Bay.

The present course of Crooked River and the basin of Sebago Lake will now be considered. Crooked River joins the Songo River a little north of Sebago Lake and the joint stream is tributary to that lake. If Crooked River is followed upstream, a surprising discovery is made: its source is only two miles from the Androscoggin near Bethel and the divide separating the two rivers is only 35 feet above the Androscoggin (Fig. 5).

The examination of Crooked River and the basin of Sebago Lake makes it appear that this route was occupied during preglacial times by a large river which flowed southerly from Bethel. This stream was formed in the vicinity of Bethel by the junction of two major streams. One of these headwater streams came from the Mount Winthrop Divide and the other from the north, probably receiving tributaries from the valleys of Sunday and Bear rivers. For convenience this preglacial stream will be referred to as the "Sebago River."

The character of the valley of Crooked River becomes of great importance when considered as a possible course of a large river. The valley is broad and has a direct course with no sharp turns. The name of the stream implies a crooked course, but the windings are all of minor magnitude; they are the meanders of a small stream flowing in a broad valley of low gradient.

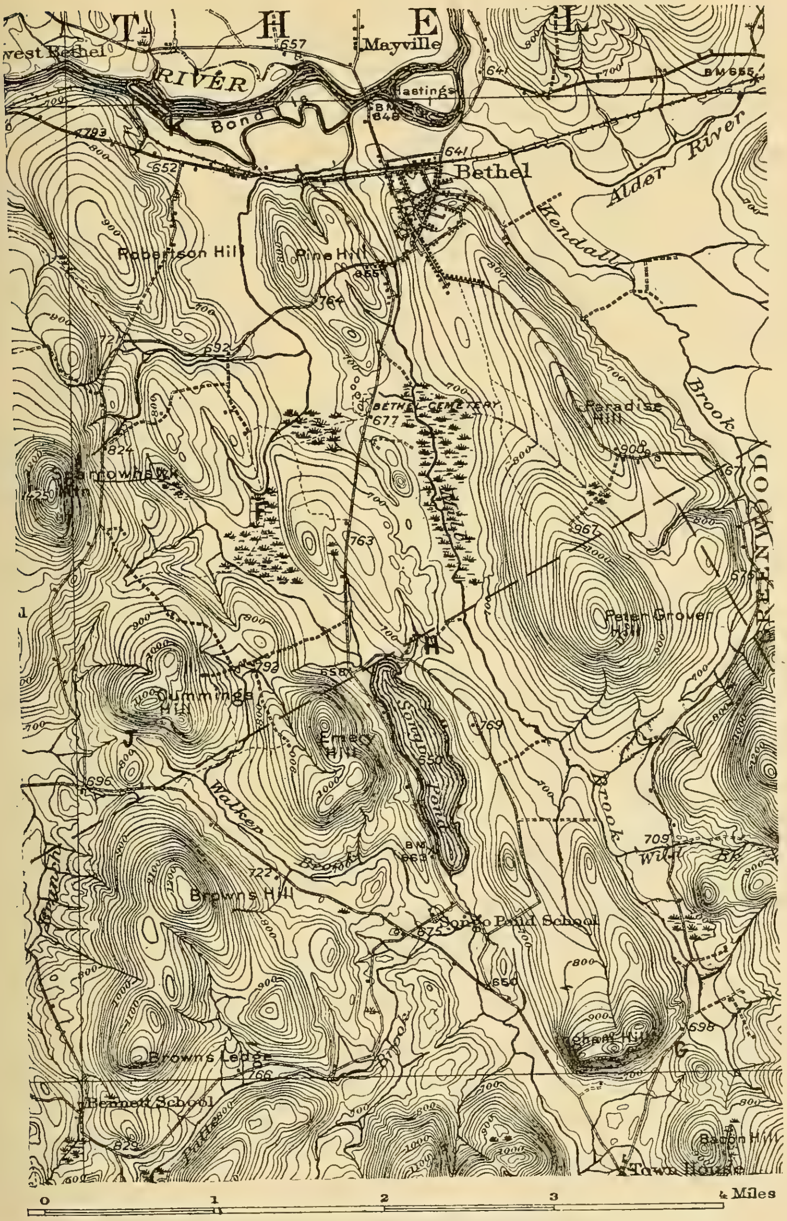

FIG. 5.—Map of the region about Bethel

On the lower course of Crooked River there are several low falls. The valley is filled with drift and in meandering across this drift plain the stream has discovered the ledges that now break its bed. The old river was probably free from falls.

At several places, in its upper part, the valley is rather narrow, but in estimating the size of valley required by the Sebago River it must be remembered that the upper Androscoggin was then tributary to the Connecticut, and the river below Bethel was smaller than the present Androscoggin. It follows that the narrow places which are in the mountains were ample for the Sebago River.

In the town of Albany, at the place marked L on Figure 1, granite bed rock outcrops in the stream at an altitude of 610 feet. The grade of the Sebago River from this point to Bethel was 3 feet per mile or the same as the present grade of the Androscoggin above Bethel.

The entire valley of Crooked River has been carefully studied with regard to narrow places, sharp bends, and elevation of bed rock, and nothing has been found tending to disprove the belief that this was the course of a large river.

There are four passes between the headwaters of Crooked River and the Androscoggin, marked *F*, *G*, *H*, and *J* on Figure 5. The lowest pass (*F* on Fig. 5) is a mile north of the head of Songo Pond. Its summit elevation is 670 feet or only 35 feet above the Androscoggin. The pass is broad, flat, and swampy, and no ledge is visible in the pass or on its slopes; there is nothing to indicate bed rock near the surface, and therefore this pass is believed to be the drift-filled valley of the old river. Songo Pond is reported to be 40 feet deep, which places its bottom 25 feet below the Androscoggin and gives further evidence of a buried valley. The other passes are higher and will therefore not be considered further.

Profile 3 (Fig. 2) shows the grade of the Sebago River from Bethel to the sea. The full line represents the present surface, and where the old river course is now buried, its probable grade is shown by a broken line. A comparison of the profile of the Sebago River with that of the present Androscoggin (Profile 1) shows that the present river has a series of stretches with very

gentle gradient broken by falls, while the Sebago River has a constant grade without falls, indicating that the present course of the Androscoggin is partly at least of recent origin and that the course of the Sebago River was for a long time occupied by a large stream.

There is no obstacle today except glacial drift to prevent the Androscoggin from following its old course and a dam 40 feet high at Bethel would enable it to do so.

Sebago Lake is drained by the Presumpscot River, a short stream with seven falls and an indirect course. It is at once seen to be a postglacial stream without a rock valley, and it can be dismissed as a possible course for the Sebago River.

On the south side of Sebago Lake is Sebago Lake Station, where the Main Central Railroad crosses a very low divide. A rise of 20 feet in the lake would cause it to overflow here. The topography is typical of a terminal moraine; kames and kettles are numerous, and there are several kettle ponds.

This morainal dam marks the preglacial outlet of the Sebago Basin and the rock valley which the moraine now fills was undoubtedly the route of Sebago River.

Between Sebago Lake and the ocean the old valley is lost under a heavy mantle of till and extensive marine deposits. There are well-developed marine terraces at several levels near the coast.

The old valley probably reached the present shore in the vicinity of Old Orchard, where there is a broad indentation of the coast with no rock outcrops over a considerable area. Offshore soundings tend to confirm this view.

The valley of Sebago River from Bethel to the ocean has been located and described as fully as conditions permit. It presented, before being clogged with glacial drift, a natural course for a large river and is more probable as the preglacial course of the Androscoggin than the present route.

The Sebago River, which made this valley, had little in common with the present Androscoggin. One branch came from the Mount Winthrop Divide to Bethel, where it joined a branch from the valley of Sunday River.

South from Livermore Falls through Lewiston the present Androscoggin has a fairly direct north-south course in agreement

with the general trend of the topography. This region has not been studied in detail, but it appears probable that in preglacial times there was a river following a course similar to that of the present Androscoggin, between Livermore Falls and Lisbon Falls, and emptying into Casco Bay. This preglacial stream with the Little Androscoggin was the principal river between the Sebago and the Kennebec.

The Androscoggin River east of the mountains now occupies parts of two preglacial drainage systems. The main valleys of these two systems were clogged with drift in many places and the resulting drainage follows a circuitous route and empties into the Kennebec with a retrograde course.

CONCLUSIONS

This study has shown that the present course of the Androscoggin River is largely postglacial in origin.

It appears that in preglacial times there was a low divide at Mount Winthrop on the northeastward continuation of the main ranges of the White Mountains. All the drainage northwest of this divide went to the Connecticut River, passing through the valley now occupied by the Upper Ammonoosuc. This drainage system, including the Androscoggin above Dummer and the stream from Mount Winthrop Divide, is here called the "Mahoosuc" system.

Eastward from this old divide a stream flowed to Bethel where it was joined by a branch from the valley of Sunday River; and the stream resulting from their union, here called the "Sebago River," flowed southward through the valley now occupied by Crooked River, through the basin of Sebago Lake and into the ocean near Old Orchard.

East of the Sebago system was a north-south stream which with its tributaries, including the Little Androscoggin, drained nearly all the region between the Sebago and Kennebec rivers.

East of Bethel the drainage lines were greatly disarranged by heavy deposits of glacial drift. A single stream may occupy portions of several preglacial valleys and have other portions of its course of postglacial origin.

The capture of the Mahoosuc River by the Sebago River is probably not due to glacial disarrangement, but is best explained as preglacial piracy by the Sebago River.

The economic effects of these drainage changes are very important. The falls at Berlin and Gorham are due to piracy; and the pirate stream has not yet eroded the valley to grade. The falls at Rumford, Livermore, Lewiston, Lisbon, and Brunswick are due to the displacement of the river by glacial deposits. These falls furnish a large amount of valuable water power and there are important mills at all the places named. Prior to the rearrangement of the drainage there was probably little if any potential water power. When the pirate stream cut through the divide it made an easy route through the mountains which is now occupied by a railroad.

NOTES ON THE SAND DUNES OF NORTH-WESTERN INDIANA

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Of the sand dunes of North America, few present more interesting phenomena than those bordering the southern shore of Lake Michigan. Not only do they illustrate all phases of dune activity but they have a significance in ecology and post-glacial history as well as rare scenic beauty. They are conspicuously developed in northwestern Indiana, their maximum development being confined to the 20 miles of shore between Gary and Michigan City. Heights of 100 feet are common and the height of the frontal ridge along the lake commonly ranges from 75 to 175 feet. Parts of the dune complex are fixed and forested, while in other areas the sand is being shifted. The dunes are limited largely to a belt about a mile wide along the shore, although in places low dunes extend several miles inland.

Along the western shore of Lake Michigan for 20 miles north of Chicago the waves are actively cutting into the thick drift, here composed of rather fine materials. This wave-cut cliff may be seen on the Highwood topographic map and in places is more than 80 feet high. A very considerable amount of erosion has taken place and some of the débris has been transported southward by the alongshore currents. Evidence of this movement is seen in the accumulations of sand on the northern sides of piers and the southerly deflection of streams entering the lake where unprotected by breakwaters. With the wear and sorting involved in the transportation, the material which reaches the southern end of the lake is almost exclusively quartz sand. Here the topography and prevailing winds are such that deposition takes place. The shore sands become the prey of the winds and the dunes reach their greatest development.

In order to examine the effect of the wind transportation on the sand grains, nearly fifty samples were gathered along seven lines

running back from the lake and at right angles to the trend of the shore. On the assumption that all of the dune sands had been blown inland from the present shore, it was anticipated that the sand would show increasing signs of wear with increasing distance from the shore. The microscope was used to determine the rounding of the grains, and for the gradations in size a tower of sieves was found most satisfactory. The customary procedure in the latter case was to weigh out 25 grams of sand and pass it through sieves of 60, 80, and 100 mesh to the inch, thus giving four grades of size, namely the sand retained in each screen and that passing through the 100 mesh sieve. These groups were then weighed and converted into percentages.

The percentage of coarse sand was found to decline back from the shore and there was a corresponding increase in the finer grades. At a distance varying from one-fourth to one-half mile from the beach, however, came a sharp increase in the proportion of coarse sand along most of the lines on which samples were taken. The change was quite regular, and reference to field notes showed that on the lakeward side of the location for each sample which showed the unexpected coarseness there was an area of muck or marsh. Subsequent field investigations showed a more or less continuous belt of this swamp or muck land between the dune belt nearest the lake and the next one to the south, the dunes to the south being lower and more rounded. Along the southern border of this flat there were in places topographic suggestions of an old beach ridge and from burrows of animals and holes which were dug, very coarse sand was found. In the analyses of the samples from the second dune belt, next south of the swamp belt, there was again a progressive decrease in size of grain grading to the south. The evidence, both topographic and petrographic, therefore points to an old shore line, the dunes immediately to the south having been built when the lake shore stood at its position, rather than having been blown inland from the present beach. The muck or marsh marks the approximate position of a former shore, and was perhaps developed behind a barrier beach.

The South Shore Electric Railway in the dune country runs parallel to the lake and about a mile south of it. Most of the dunes are north of the railroad but for much of the distance there

is a definite beach ridge, together with low dunes, just south of the road. Analyses of sand along section lines through this third belt of dunes showed an increase in the size of grain as compared with the sand immediately to the north, and on later search shells and pebbles were found. The evidence for a former strand line in this position is strong.

South of the third dune belt just referred to, especially in the neighborhood of Johnsville, there is another pronounced beach line banked with low dunes on the south. The beach here is well marked and strewn with beach-worn pebbles. None of these shore-line evidences were anticipated but were first suggested by variations in the coarseness of the sand. Since the interruption in the gradation of size was a rather regular phenomenon and scarcely to be accounted for if the sand had been subjected to greater wear, search was made for additional evidence of shore lines. In connection with each of the three suspected beach lines, additional criteria were found in the form of beach gravels or coarse sands, and in the case of the two beaches most distant from Lake Michigan the topographic evidence was strong.

The history of the dunes therefore appears to be closely associated with the development of Lake Michigan. With the northward retreat of the Late Wisconsin ice sheet a lake was formed in the Michigan basin, known as Lake Chicago. Since the present northern outlet was blocked by the ice, the water level was higher than now, the overflow being to the south through the Illinois River, as is well known. With the lowering of this channel and the uncovering of other outlets by the retreating ice front, there followed successive levels of the water. These halts are known as the Glenwood, Calumet, and Tolleston stages of Lake Chicago, the level of the water above Lake Michigan being respectively 56, 32, and 17 feet. In the absence of topographic maps or precise elevations in the area under consideration, determinations of the elevations of the old shore lines have not been made. Judging from the gradient of the two streams which cross the dunes and by the positions of the beaches in adjacent areas, it is thought best to assign the four belts of dunes to the various stages in the history of the lake, including the present. On this basis, each dune belt in the complex

dates back to a distinct period in post-glacial history, and while sand from one tract has been blown into the other belts, in places obscuring the evidence of a beach, each tract is on the whole distinct.

The exact locations of the shore lines have not been mapped in the region involved, and in some places this will be impossible because of the moving dunes; their approximate position, however, is as follows: Tolleston Beach passes through the southern border of Miller and along the southern margin of Long Lake. At Wicliffe it is doubtless north of the station on the electric line and beginning with the eastern border of the broad opening through the dunes at Wilson it is marked by the southern edge of the marsh or muck tract within the main body of the dunes; this continues almost to Michigan City. The Calumet Beach is just south of the Little Calumet River in Lake County, and as far west as Wilson where Lake Chicago had an extensive embayment. Beyond this it parallels the South Shore Electric Railway as far as Johnsville, being immediately south of it. The Glenwood Beach is south of the Michigan Central Railroad in the eastern portion of Porter County and after swinging south in a semicircle about the former embayment, strikes west south of Hobart, some seven miles from Lake Michigan.

Due to the complex processes which have shaped the sand it is difficult to make more than generalizations as to the rounding and polishing of the grains, and shifting winds render it impossible in some places to ascertain whether the sand at any given point has recently arrived or is part of the original material of the dune. Microscopic examination of the beach sand shows it dominantly subangular. It is generally rather transparent and little pitted, the corners frequently being sharp with little rounding. Back from the beach the characteristic description would be subspherical, many of the grains being well rounded and bean-shaped. All sand which has been subjected to sand-blast action is pitted and frosted, this being quite noticeable in the dune sand. Within the older dune belts this gradation from the former shore line landward is also apparent, but on account of the longer period of exposure and consequent aeolian wear of all the sand, the contrast between beach and dune sands is here less pronounced.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Berek, M. "Zur Messung der Doppelbrechung hauptsächlich mit Hilfe des Polarisationsmikroskops," *Centralbl. f. Min. Geol. u. Pal.*, 1913, 388–96, 427–35, 464–70, 580–82. Figs. 7.

The new Berek compensator here described is somewhat similar in pattern to the Nikitin quartz compensator. In the present case, however, the mineral plate is calcite. The author shows that the dispersion of mineral sections nearly at right angles to the optic axis becomes practically zero, consequently any inactive, uniaxial mineral is suitable. Since rather a thick section is required to give the higher orders of colors, quartz cannot be used on account of its rotary polarization. The construction of this instrument permits much more accurate measurements than that of Nikitin. A calcite plate, 0.1 mm. in thickness, cut at right angles to the optic axis, is attached to a rotatable axis in a slider which is to be inserted in the slot in the microscope above the objective. Since it is thus between the polarizing prisms, no cap nicol is required. The amount of rotation of the plate is read from a graduated drum and vernier to 2′. With the thickness of calcite used, it is possible to read colors to the fourth order. If higher readings are desired, the calcite plate may readily be removed and replaced by one that is thicker. The sensitiveness of this compensator is shown to be equal to that of Babinet for moderate double refraction, and greater for low colors.

Berek, M. "Über Zirkularpolarisation," *Fortschr. d. Min., Krist., u. Petr.*, IV (1914), 73–114, 221–62. Fig. 1.

A full discussion of the phenomenon of rotary polarization.

Berek, M. "Die astigmatischen Bildfehler der Polarisationsprismen," *Centralbl. f. Min. Geol. u. Pol.*, 1919, 218–24, 247–55, 275–84. Figs. 5.

The insertion of the nicol prism between the objective and ocular causes astigmatic and focal disturbances. The latter is usually com-

pensated by means of a lens above the analyzer, but the former has hitherto been left uncorrected. In this paper the cause of the astigmatism is discussed and lenses for its correction are suggested. Two photographs of the same slide show the remarkable improvement in definition with the corrected nicol.

BEREK, M. "Über die Berechnung der Polarisationsverhältnisse im Gesichtsfelde der Polarisationsprismen," *Verhandl. d. Deutschen Physikal. Gesell.*, XXI (1919), 338–46.

BEREK, M. "Die Schärfentiefe des Mikroskops," *Zeitschr. f. wissensch. Mikroskopie*, XXXVII (1920), 120–22. Fig. 1.

BEREK, M. "Uber die einfachen und zusammengesetzten charakteristischen Konstanten der Mikroskopobjektive," *Zeitschr. f. wissensch. Mikroskopie*, XXXVII (1920), 36–41. Figs. 2.

A discussion of the use of 250 mm. and Δ in the determination of the enlargement of objectives.

BERKEY, CHARLES P. "Geological Reconnoissance of Porto Rico," *Ann. N.Y. Acad. Sci.*, XXVI (1915), 1–70. Figs. 20, maps and profiles 2.

This is a report of the New York Academy of Sciences Expedition to Porto Rico undertaken, in part, to determine the nature and origin of the rock formation and to group them into series suitable for use in subsequent geological work. Two series are described—a younger, consisting of Tertiary shales, reef limestones, and recent deposits, and an older including tuffs, ashes, shales, conglomerates, limestones, and a great variety of probably pre-Tertiary intrusives. Igneous rocks described briefly are extrusive basalts and andesites, and intrusive andesite-prophyry, granite-porphyry, granite, and diorite.

BOEKE, H. E. "Die Eisenerze," *Die Umschau*, XXIII (1919), 289–92.

A popular article on the occurrence of iron ore.

BOWEN, N. L. "Differentiation by Deformation," *Proc. Nat. Acad. Sci.*, VI (1920), 159–62.

Discusses differentiation according to Darwin's theory of fractional crystallization and the squeezing out of the mother liquor.

BOWEN, N. L. "The Sodium-Potassium Nephelites," *Amer. Jour. Sci.*, XLIII (1917), 115–32. Figs. 2.

While this is strictly a mineralogical paper, it is of importance to petrographers in showing the inaccuracy of calculating nephelite as $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$. It is here shown that the molecules $NaAlSiO_4$ and $KALSiO_4$ are fundamental constituents of it, although they may be present in variable amounts.

BRAUNS, R. "Skapolithführende Auswürflinge aus dem Laacher Seegebiet," *Neues Jahrb.*, B.B., XXXIX (1914), 79–125. Pls. 2.

Describes seventeen different kinds of scapolite rocks from the Laacher Sea region. Numerous analyses are given.

BRAUNS, R. "Der Laacher Trachyt und seine Beziehung zu anderen Gesteinen des Laacher Seegebietes," *Neues Jahrb.*, B.B., XLI (1916), 420–502. Pls. 2.

This is a very complete study of the Laacher Sea trachyte and related rocks. Twenty-three new analyses are given, all of which are also recast into molecular proportions reduced to 100, and computed according to Osann's system. Nine older analyses are quoted for comparison. A history of volcanic activity in this region is given, and the following conclusions as to the relationships of the rocks are reached: The white pumice, the Dachsbusch trachyte, and the light Laacher trachyte are so closely related chemically that they are thought to have been derived from the same magma, their differences in habit being due to the action of the inclosed gases. Petrographically they may be designated phonolitic trachytes and trachytic phonolites. Further, these rocks are closely related chemically to the adjacent noselite-phonolites, and it is probable that they came from the same magma, their differences being due perhaps to greater differentiation or to assimilation of crystalline schists. The dark Laacher trachyte is more

closely related to the tephrites of the region, and it is assumed that the trachyte assimilated some of its constituents. The oldest and at the same time most basic rocks of the region are the tephritic lavas. These are followed by younger and progressively more acid noselite-phonolite, white pumice, and finally light trachyte. Among the ejectamenta are fragments having the character of dike rocks, some of which are more basic than the tephrites, and others more acid than the Dachsbusch trachyte. Fragments of plutonic rocks, so far as these have been analyzed, show intermediate chemical characters. The rocks are all fully described and only lack estimates of the mineral percentages to present good word-pictures of their appearance.

BRAUNS, R. "Neue skapolithführende Auswürflinge aus dem Laacher Seegebiet," *Neues Jahrb.*, I (1917), 9–44. Pls. 2.

Nine more scapolite-bearing rocks from the Laacher Sea region are described. There are many analyses, and a determination of the refractive index of the sulphate scapolite.

BRAUNS, R. "Über aufgewachsene Karlsbader Zwillinge von Sanidin vom Laacher See," *Neues Jahrb.*, I (1917), 45–49. Pl. 1.

BRAUNS, R. "Einige bemerkenswerte Auswürflinge und Einschlüsse aus dem niederrheinischen Vulkangebiet," *Centralbl. Min. Geol. u. Pal.*, 1919, 1–14. Fig. 1.

BRENNER, TH. "Über Theralit und Ijolit von Umptek auf der Halbinsel Kola," *Bull. Com. Géol. Finlande, No. 52*, 1920, 1–30. Figs. 4.

Here are described the Kola Peninsula theralite, and a new ijolite from the Tachtarwun Valley. The descriptions are elaborate and good with the exception of the omission of an estimate of the mineral percentages in the theralite. Omissions of this kind lead to such errors as the statement that "es giebt sowohl grobkörnige, helle als kleinkörnige, dunkle Arten." But theralite is a name given by Rosenbusch to certain nephelite, plagioclase plutonic rocks which he thought were represented by certain tephrites and basanites described by Wolff from the

Crazy Mountains. As a matter of fact, they were first found some years later by Wolff in Costa Rica. While in his first published description Rosenbusch does not make the predominance of the dark constituent a necessary qualification, in his later works he grouped the theralites and shonkinites, and said of them: "Die Theralithe und Shonkinite sind hypidiomorphkörnige Tiefengesteine, welche *bei starker Vorherrschaft der dunklen Gemengtheile* durch die Mineralcombination Nephelin mit Kalknatronfeldspath, bezw. Nephelin mit Kalifeldspath, charakterisirt sind," consequently there can be no light theralites. The analyses of various theralites are recast into both the C.I.P.W. and Osann's system. The ijolite is described fully and analyzed. It differs from the usual ijolites in the presence of arfvedsonite-hornblende. The modal percentages determined by the Rosiwal method are: nephelite 38.25 per cent, arfvedsonite-hornblende 31.96 per cent, aegirite-augite 16.24 per cent, titanite 5.78 per cent, mosandrite 3.81 per cent, magnetite 2.37 per cent, apatite 1.59 per cent. The rock, consequently, may be classified as 3126 (new form, or 3131 old form) of the reviewer's system. The chemical analysis of the rock is computed in the C.I.P.W. system as Ivaaros, and is compared with three other ijolites, one a Malignos, one an Ivaaros, and one an Ijolos. In an appendix are given analyses of fifty-four theralites and related rocks.

REVIEWS

The Geology of Hardin County and the Adjoining Part of Pope County. By STUART WELLER with the collaboration of CHARLES BUTTS, L. W. CURRIER, and R. D. SALISBURY. Illinois Geological Survey, Bull. No. 41, 1920. Pp. 377, pls. 11, figs. 27.

This report represents the results of three seasons' field work by the author in conjunction with Messrs. Butts and Lee of the U.S. Geological Survey and part of two seasons by Mr. Currier in the study of the fluorspar deposits of the county. In addition a chapter on the geography of the region is contributed by Mr. Salisbury.

Hardin County lies in the southeastern part of the state and wholly within the Ozark country, an area of considerable relief and in a mature stage of dissection. The history of the topography involves four periods of uplift, the three cycles of erosion other than the present one, being known as the Karber's Ridge, McFarlan, and Elizabethtown cycles.

Structurally the area is characterized by rather flat-lying strata surrounding an area of doming and intense faulting. The faults are of the normal type and form a network along the edges of the dome which is roughly circular in outline. They originated through the collapse of the dome. Likewise remarkable is the presence within the region of igneous intrusives in the form of dikes, sills, and plugs. The origin of the dome involves the intrusion of these rocks, the collapse following either the gradual spreading out of the lava or its partial withdrawal. The structure is remarkable and has but few known parallels.

The rock formations of the region include Devonian, Mississippian, and Pennsylvanian sediments, involving a thickness of some 4,000 feet. Of special note is the contribution to the knowledge of the Chester group.

The oldest formation present, known locally as the Devonian limestone, is correlated with the Lower Devonian, Onondaga, and Hamilton. Lithologically it is a unit. The overlying Chattanooga shale contains but a meager fauna and from its stratigraphic relation may be correlated with either the Upper Devonian or Lower Mississippian, or both.

The Meramec group, as originally defined by Ulrich, included the Warsaw, Spergen, and St. Louis limestones. A study of the Ste. Genevieve faunas convinces Professor Weller that this formation is much

more closely related to the St. Louis group than to the Chester with which Ulrich had allied it, chiefly due to the presence of a species of the typical Chester genus *Coeloconus*. On this basis and the recent recognition of an unconformity separating the Renault and Ste. Genevieve formations, Weller redefines the Meramec group so as to include the Ste. Genevieve.

This report represents the most recent work on the subdivision of the Chester and the correlation of these units. Especial attention is called to the following corrections of previous correlations of the formations of southeastern Illinois and Kentucky with those of Randolph County: (1) the Renault and Shelterville formations, the Upper Ohara of Ulrich, are correlated with the Renault. Professor Weller considers those species of the genus *Talarocrinus* with the thickened plates forming bilobed basis as very characteristic of the Lower Chester. This fauna is typically developed in the Upper Ohara; (2) the Golconda limestone with the Lower Okaw; (3) the Cypress sandstone with the Ruma; and (4) the Bethel sandstone with the Yankeetown formation. Methods of correlation are discussed in detail.

The igneous rocks of the region are found chiefly in the vicinity of the Ohio River where the more rapid erosion has exposed them. They are of three types: fine-grained, dark-colored lamprophyres, medium-grained, dark-colored peridotites, and volcanic breccia.

Economically Hardin County is noted for its fluorite deposits, the annual output of the county being over two-thirds that of the country. Fluorite occurs as (1) vein deposits, replacing calcite fillings of the fault planes; (2) bedded deposits where fluorite has replaced limestone bedrock; and (3) superficial residual deposits. Small quantities of lead and zinc are recovered incidental to the fluorspar exploitation. The origin of the deposits involves (1) doming and faulting in post-Pennsylvanian, (2) deposition of calcite in the fault fissures, (3) mineralization by fluriferous magmatic solutions replacing calcite, and (4) the introduction of metallic sulphides.

The only other large resource of the region is agriculture. There is an abundance of limestone suitable for lime, cement, and ground rock for fertilizer, as well as an unlimited supply for road metal. In regard to the oil and gas possibilities, while the structure is favorable, but little is known of the underlying pre-Devonian sediments.

In the portion of the bulletin devoted to systematic paleontology, the work is limited to those common species in need of further illustration and description and to those forms important for their bearing upon

the correlation problems. The majority of these are Chester forms, together with some Ste. Genevieve and St. Louis species. Of interest is a new species of *Septopora, S. similis* from the lower St. Louis which is almost identical in character with the Chester *S. subquadrans*. This occurrence is noteworthy in that the genus *Septopora* has hitherto been considered highly characteristic of the Chester. Seventy-two species are described and figured, prominent among which are species of *Talarocrinus* and *Pentremites*.

A. C. McF.

On the Crinoid Genus Scyphocrinus and Its Bulbous Root Camarocrinus. By FRANK SPRINGER. Memoir Smithsonian Institution, 1917. Pp. 74, pls. 9, figs. 16.

For more than a half-century there have been known to paleontologists certain bulb-like, supposedly crinoidal or cystoidal, bodies which were described from American localities in 1869 by Hall as *Camarocrinus*. Similar structures had been known for some time from the Silurian of Bohemia where they had been found by Barrande. He had named them *Lobolithus* without describing them.

In 1904 Schuschert summarized all the known facts touching the occurrence and relations of this form. He found that these structures were of widespread occurrence in both Bohemia and America. In the former they were confined to a horizon equivalent to the American Rochester shale, and in the latter to the Manlius and Helderbergian. In Bohemia they were commonly associated with the genus *Scyphocrinus* which was as yet undescribed from America. They were frequently found in beds void of any other crinoidal remains and a large majority were found in strata with their stalked end down. He came to the conclusion that

> *Camarocrinus* thus appears to be the float of an unknown crinoid, that was held together after the death of the individual by the firmly interlocked double walls of the exterior and interior, while the crown and stalk dropped away. Under this hypothesis the float drifted with the sea currents, was finally filled with water and, the attenuated end being heavier, sank in that position.

It is the purpose of this paper to present the results of some later studies by Mr. Springer which have resulted in a change in the conception as to the functional nature of the so-called *Camarocrinus*. He finds not only that the genus *Scyphocrinus* does occur in abundance in America but that the *Camarocrinus* bulbs are directly connected at the distal end of the stem of crinoids belonging to that genus. Moreover

these bulbs, when in their original position, occur with the stalked end upward and not downward as previously supposed, the bulb being merely a distal specialization of a true root and not a float.

The bulb-like process may itself be described as a

> rigid, hollow, chambered root, consisting of a large spheroidal bulb with a short projecting collar, a stem base with bifurcating roots resting in and forming a large part of the floor within the collar; and several internal, laterally opposed sacs which abut against the inner side of the bulb wall. . . . . The collar and bulb wall consist of single layers of similar plates derived from rootlet systems originating at the ends of the proximal root branches.

Eight species of *Scyphocrinus* occurring in America are described and are figured together with several species of other genera. A table of analysis of the American forms is given.

A. C. McF.

The American Species of Orthophragmina and Lepidocyclina. By JOSEPH A. CUSHMAN. Shorter Contributions to General Geology. U.S. Geological Survey, Professional Paper 125 D, 1920. Pp. 39–108, pls. 7–35.

The genera *Orthophragmina* and *Lepidocyclina* belong to the group of orbitoid *Foraminifera*, a group of excellent horizon-markers due to their limited stratigraphic range, wide geographic distribution, and great abundance in the Tertiary. Hitherto the group has received but little attention by American paleontologists. In the present paper the author describes all known American species, which form but a small percentage of those which he believes will be later described and have been described from the European Tertiary.

Orthophragmina includes those species characterized by the presence of rectangular chambers in the equatorial band. The genus is limited, so far as known, to the Eocene, and in America, chiefly to the upper part. *Lepidocyclina* differs in that the chambers of the equatorial belt are typically hexagonal. It ranges through the Eocene, and Lower and Middle Oligocene.

Sixteen species of *Orthophragmina* are described, of which two are new, and thirty species and varieties of *Lepidocyclina* of which eleven are new. The author includes a table of tentative correlations of the Tertiary of Panama by T. W. Vaughan, a key to the species of *Lepidocyclina* and a list of those species which are considered as good index forms for the Tertiary of the Coastal Plain.

A. C. McF.

North American Early Tertiary Bryozoa. By FERDINAND CANU and RAY S. BASSLER. United States National Museum, Bull. No. 106, 1920. Pp. 878, pls. 162, figs. 279.

This monograph forms a pioneer work in the field of American bryozoölogy. Despite the great abundance and splendid preservation of bryozoa along the Atlantic and Gulf Coast regions, there has hitherto been so little done with them as to leave the field almost virgin.

Under the term Lower Tertiary the authors have included the Midwayan, Wilcoxian, Claibornian, Jacksonian, and Vicksburgian formations. There is found here a much richer bryozoan fauna than in the succeeding formations. A study of the Miocene, Pliocene, and Pleistocene bryozoans has been completed and it is hoped that it will soon appear as a monograph supplementing the present work. An extensive table showing the geographic and stratigraphic distribution of the different species is given.

Tertiary bryozoans are so intimately related to living forms that a thorough knowledge of the taxonomy and anatomy of living species is necessary for the proper classification and interpretation of the structures found. Accordingly the authors have produced a monograph which is of use both to the zoölogist and to the paleontologist. Numerous text figures are introduced to make the report of value to the non-specialist. A detailed discussion of the structure and classification of living forms is given.

With the exception of one undetermined species, referred to the order *Ctenostomata*, all Tertiary bryozoans belong either to the *Cheilostomata* or *Cyclostomata*, the latter being about half as numerous as the former. These are included in the subclass *Gymnolaemata*, which includes all fossil bryozoans, and is characterized by a circular row of tentacles surrounding the mouth. It is in turn incorporated in the class *Ectoprocta* which is distinguished by the presence of the anal orifice outside the row of tentacles.

The *Cheilostomata* which were probably derived through the Paleozoic *Trepostomata*, differ from the *Cyclostomata* in that they may be either calcareous or chitonous, and the aperture is closed, upon the retraction of the polypide, by an operculum. The *Ctenostomata* are chitonous or gelatinous forms with the aperture closed by a tooth-like process.

The studies of the authors have led them to discard for the present the former major classification of the *Cyclostomata*, retaining for convenience only the two larger divisions the *Ovicellata* and *Inovicellata*. In classifying the *Cheilostomata* orders were based upon general mor-

phology, suborders on the form of aperture and operculum, and families on the presence of cardelles, lyrula, ovicells, and radicells.

With the increased recognition of the value of bryozoans as horizon-markers, the student will find this systematic report a reference of constant value.

A. C. McF.

Louisiana Lignite. By Robert Glenk. Department of Conservation, Division of Economic Geology, State of Louisiana, Bull. No. 8. New Orleans, 1921.

Although Louisiana lignite has been consistently mapped on all fuel maps of late years as a possible source of low-grade fuels, it has not until recently begun to receive the attention that it merits. The report here reviewed shows a gratifying interest by the state of Louisiana in its available resources—an interest that, since the days of Harris' and Veatch's work on the state survey, appeared to have flagged.

The lignite of Louisiana is of Eocene age and distributed vertically in the Wilcox, Claiborne, and Jackson groups. It varies in thickness from a few inches to twenty feet. Interesting paleobotanical collections have been made from it. In the adjacent states of Texas and Arkansas lignite is mined in considerable quantities by stripping the overburden, or by the room-and-pillar method where the dip of the lignite bed is appreciable; similar methods, though not yet used in Louisiana, might well be applied there in the future.

Figures expressing the lignite reserves of the state are not presented; they would be interesting and useful. Analyses of several Louisiana lignites yielded the following:

	Percentage
Moisture	5–47
Volatile combustible matter	30–75
Fixed carbon	5–40

The highest thermal value obtained was 8,046 B.T.U.'s. The analyses presented show Louisiana lignite to be of an intermediate grade. With destructive distillation the end products were:

	Percentage
Aqua ammonia	20 –30
Tar	4.5– 5
Carbonized residue	50 –56
Gas and loss	18 –20

The carbonized residue has a heating value equal to good anthracite; an average ton of lignite yields 8,000 cubic feet of gas (mainly hydrogen,

methane, and carbon monoxide) with a heating value of 450 B.T.U.'s per cubic foot; this is a higher value than producer gas or Mond gas, but lower than coal gas or natural gas.

In general it appears that the chief use to which Louisiana (and probably all Gulf Coast) lignite can be put is in the briquetting of the carbonized lignite, with the recovery of the tar and ammonia as by-products and the utilization of the gas in producing electric power. Such a use avoids the difficulties involved in shipping and storing the combustible fuel, and makes available to the Gulf States, where hydraulic power is not always obtainable, a cheap source of electricity.

The report, although in a large measure a compendium of other works on the subject, presents a series of original and very careful fuel analyses, and is a most valuable addition to the scanty information on the subject of the geology and technology of utilizing Louisiana lignites.

C. H. B., Jr.

A Glossary of the Mining and Mineral Industry. By ALBERT H. FAY. U.S. Bureau of Mines, Bulletin 95. Pg. 754. Washington, 1920.

This glossary constitutes a noteworthy contribution to mining literature. It contains about 20,000 terms; these include both technical and purely local terms, relating to metal-mining and coal-mining, quarrying, and the recovery of petroleum and natural gas, as well as many metallurgical terms. It includes also the names of useful and important common minerals and rocks, and geological terms. The glossary presents, in a single comprehensive volume, essentially all of the terms in use in the mineral industries in English-speaking countries, together with most of the Spanish terms in use in the United States and in Latin America. In addition it includes terms relating to ceramics and glass-making, foundry practice, railway and building construction, electrical installation and power-plant equipment, and chemical terms relating to metallurgical practice.

E. S. B.

Geology of the Yellow Pine Cinnabar District, Idaho. By E. S. LARSON and E. C. LIVINGSTON. U.S. Geological Survey, Bulletin 715 E. Pp. 12. Washington, 1920.

The Yellow Pine cinnabar district, in Valley County, Idaho, is about 70 miles from the town of Cascade. The cinnabar ore bodies appear to be in irregular lenses or chimneys of silicification in limestones which have been intruded by dikes and irregular bodies of rhyolite

porphyry, and the cinnabar, which is the chief sulphide in the ore, lies in part in chalcedonic silica, and in part in friable marble adjoining such silica. Some pyrite is present with the cinnabar in most of the deposits. Stibnite is present in the district, in association with cinnabar, but was not observed in any of the workable deposits.

Cinnabar was discovered in this district in 1902, and prospecting has been active since that time. In 1917 active development on a small scale was in progress.

E. S. B.

Coal in 1918. Part A: Production. By C. E. LESHER. "Mineral Resources of the United States, 1918," Part II. Washington: U.S. Geological Survey. 118 pp. 1920.

A noteworthy feature of this report, as contrasted with reports for preceding years, is the detailed statistical study, by states and for the United States, of the causes of loss of time in the coal-mining industry. In a series of instructive diagrams for the United States and for each state, the percentage of time lost on account of (*a*) car shortage, (*b*) labor shortage and strikes, (*c*) mine disability, (*d*) lack of market are separately shown. These statistical studies are timely because they throw light upon the causes of the industrial troubles which have vexed the coal industry in recent years.

E. S. B.

Some Principles Governing the Production of Oil Wells. By CARL H. BEAL and J. O. LEWIS. Bureau of Mines, Bull. No. 194, Petroleum Technology 61, 1921.

We are constantly reminded that the resources of petroleum in the United States are diminishing at an alarming rate. The fact that more oil was produced in the United States during the month of March, 1921, than during any previous month suggests that efforts to curtail production are futile. One of the best remedies for this situation is to make the most of what we have. In this we have been very successful through the Bureau of Mines.

Mr. Carl H. Beal and Mr. J. O. Lewis, the authors of this new publication, were among the first to make intensive studies of underground conditions in oil fields, so that the maximum production might be obtained from oil wells. The results have been gratifying and have more than paid for the cost of investigations.

The bulletin is a summary of all the known factors controlling the production of oil, and contains some of the theoretical aspects of oil production. It is of inestimable value to operators and "resident geologists."

W. O. G.

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Post-glacial Lakes in the Mackenzie River Basin, Northwest Territories, Canada. By A. E. CAMERON.

The Early Pre-Cambrian Formations of Northern Ontario and Northern Manitoba. By E. L. BRUCE.

Dinosaur Tracks in Hamilton County, Texas. By W. E. WRATHER.

A Scale of Grade and Class Terms for Clastic Sediments. By CHESTER K. WENTWORTH.

The Pre-Cambrian of Western Patricia. By E. M. BURWASH.

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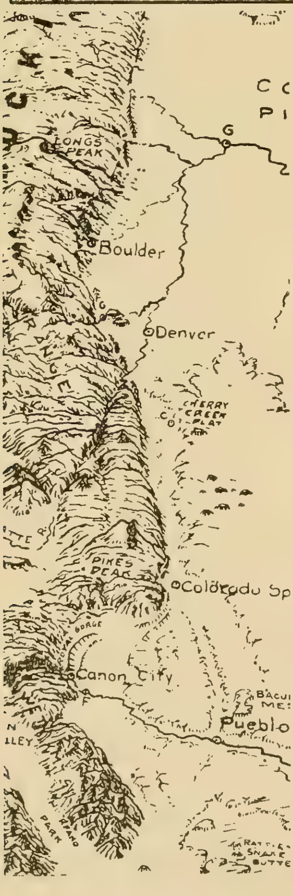
Problems in Stratigraphy along the Rocky Mountain Trench. By FRANCIS PARKER SHEPARD.



PHYSIOGRAPHIC DIAGRAM (F THE UNITED STATES

Size 62×44 inches, Scale 50 miles to one inch

By A. K. LOBECK
Department of Geography, University of Wisconsin

This diagram is intended to be used as a guide in teaching the physiography and geology of the United States. The topographic features are expressed with the ea of revealing or suggesting the underground structure, and the general charact of the underlying rock.

An introductory drill such as having students draw cross sections through he Adirondack uplift, the Cincinnati or Nashville Domes, across the Appalachia in different places, through the Black Hills, Central Texas, the Ozarks, Wisconsin nd many other regions is followed up with the use of other available material, pecially state geological maps and the United States Geological Survey topographic sheets.

The student frequently fails to note the significance of a locality with relatio to the physiographic province or geological region as a whole. This is overcom by requiring the student to locate upon the diagram the position of the topographic quadrangles under consideration. As practically every topographic map publ ed by the Survey was consulted in the preparation of the Diagram, most of the si it-cant features are recognizable in the Diagram too. Seventeen geological prov es are discussed briefly on the map.

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ON CONTACT PHENOMENA BETWEEN GNEISS AND LIMESTONE IN WESTERN MASSACHUSETTS

PENTTI ESKOLA
Geophysical Laboratory, Carnegie Institution of Washington

CONTENTS

INTRODUCTION

The eastern part of Berkshire County in western Massachusetts is underlain by a vast area of granitic gneiss, known as the *Becket granite gneiss*.[1]

[1] B. K. Emerson, "Geology of Massachusetts and Rhode Island," *U.S. Geol. Surv., Bull. 597* (1917).

In older papers by the same author, "Geology of Old Hampshire County, Mass.," *U.S. Geol. Surv., Mon. 29* (1898), and "The Geology of Eastern Berkshire County, Mass.," *U.S. Geol. Surv., Bull. 159* (1899), this granite gneiss is designated in part as "Becket conglomerate gneiss" and in part as "Tyringham gneiss."

This gneiss has been regarded as of pre-Cambrian age and the Cambrian and Ordovician rocks that bound it on the west and the east have been thought to lie unconformably upon it.

On its western side, in the Housatonic Valley, the main rock is limestone, called *Stockbridge limestone*, interbedded with quartzite and slate, while on the eastern side there is an area of highly metamorphic schists.

Within the area of the Becket gneiss there are several vertical layers (up to six hundred feet broad) of limestone, which is older than the gneiss. The most important of them, according to Emerson, are situated at Coles Brook in Middlefield, north of Becket Station in Becket, in Washington and Peru, in Hinsdale, and in the valleys of East Lee, Tyringham, and Otis. All the limestone formations within the Becket gneiss area are called *Coles Brook limestone* from the type occurrence at Coles Brook in the northeastern part of the mass. A striking topographical feature of these occurrences of limestone is that they occupy long, narrow valleys in the gneiss highland.

Near the contacts with this limestone the Becket gneiss shows two kinds of endomorphic contact phenomena: In many cases the boundary type of gneiss grows more basic and is called *Lee quartz diorite*. But in other places, the boundary type of gneiss is rich in salic minerals and contains monoclinic pyroxene and titanite. It is called by Emerson "*titanite-diopside diorite aplite*," and is supposed by him to represent a product of assimilation of the limestone by an igneous magma.

During a trip to western Massachusetts in July, 1921, the present writer, together with Dr. N. L. Bowen, had the opportunity of studying outcrops and collecting samples of these contact rocks around Benson Pond east of Washington Station, on the railroad line between Washington and Becket stations, north of Becket Station and in the valley of Goose Pond Brook near East Lee.

As the problem concerning the assimilation of limestone by igneous magmas is now being much discussed, this very instructive case may be of some interest to petrologists. A brief note of field observations and of a microscopic study of the materials collected is therefore given in the present paper together with a discussion of the results.

Numerous questions as to why and how the contact rocks have obtained their present characters arise from such studies, but to many of them no definite answers are yet possible. It often seems wiser to direct our efforts toward finding a sound form of the question, according to Bacon's advice: "Bene interrogatum quasi dimidium responsi." These questions, one may hope, will be cleared up either by future experimental investigation or by accumulating more evidence from natural rocks.

The questions to be discussed in the present paper are: Why is limestone sometimes assimilated by magmas, and sometimes not? What are the factors controlling the formation of silicate minerals in limestone during metamorphism? What laws control the distribution of elements, such as Mg and Fe, which replace each other in solid solutions, among different mineral groups, pyroxenes, amphiboles, and micas, in silicate rocks?

I wish to express my best thanks to Dr. N. L. Bowen for pleasant companionship during the excursions and for many discussions, and especially for his trouble in making the necessary grammatical corrections in my writing.

This work has been carried out with pecuniary assistance from the Geophysical Laboratory of the Carnegie Institution of Washington and from two funds for the advancement of scientific research in my native country, Finland, namely, Alfred Kordelin's General Trust for the Advancement of Progress and Knowledge, and Herman Rosenberg's Travelling Bursaries Trust of the University of Helsingfors.

BECKET GRANITE GNEISS

Emerson[1] gives the following description of the Becket granite gneiss:

> It is a medium to fine grained light-colored biotite (or biotite-muscovite) microcline-oligoclase gneiss, with microscopic epidote uniformly blended with the scanty biotite, and the microcline grains commonly grouped as if made of the crushed fragments of larger porphyritic crystals. There are small areas of light-colored porphyritic granite from which the prevalent rock could have been produced by crushing. A micrographic texture is common. Over large

[1] *U.S. Geol. Surv., Bull. 597*, p. 154.

areas the dark constituent is in whole or part magnetite in small octahedra. . . . . At its contact with the graphitic rocks the rock is commonly graphitic, and against the limestone it contains in many places secondary calcite grains and tremolite or actinolite.

The following chemical analyses of the Becket gneiss and a related gneiss have been published:[1]

I. Gneissoid granite, Alderman's quarry, Becket, Toscanose-lassenose. Analysis by G. Steiger. Specimen in Petrographic Reference Collection of U.S.G.S. No. 1649.

II. Granite gneiss, Hoosac Mountain. Toscanose. Analysis by E. T. Allen. Specimen *P.R.C.* 1718. Collected by J. E. Wolff. Consists of quartz, microcline, albite, muscovite, biotite, magnetite, titanite, epidote, apatite, zircon.

III. Composite sample of Becket gneiss from 33 localities in the Sheffield quadrangle. Collected by Joseph Barrell and analyzed by R. C. Wells.

	I	II	III
SiO_2	70.62	67.12	68.56
Al_2O_3	15.31	14.97	14.53
Fe_2O_3	1.06	2.61	1.41
FeO	0.43	2.19	2.91
MgO	0.29	0.54	0.60
CaO	1.30	1.69	2.69
Na_2O	4.55	3.92	3.58
K_2O	4.01	5.15	3.62
H_2O-	0.16	0.19	0.06
H_2O+	0.72	1.13	0.97
TiO_2	0.29	0.37	0.55
CO_2	0.88	....	trace
P_2O_5	0.07	0.14	0.17 ZrO_2 0.02
MnO	....	0.02	0.03 S 0.03
BaO	....	0.19 ZrO_2 0.03	0.07 F 0.02
	99.69	100.26	99.82

Through the courtesy of Dr. E. S. Larsen of the United States Geological Survey, I had the opportunity of studying the original specimen of Analysis I, the Becket gneiss from Alderman's quarry. It is a light gray granite, rich in muscovite. All its minerals are clear and unaltered.

In the plagioclase were determined $\beta_D = 1.5345 \pm 0.001$; $\alpha'_D = 1.532 \pm 0.002$; $\gamma'_D = 1.540 \pm 0.002$,[2] corresponding to Ab_{92}.

[1] F. W. Clarke, *U.S. Geol. Surv., Bull. 591*, pp. 33–34.

[2] The composition of the plagioclases, in this study, was ascertained mainly from the indices of refraction determined in rock powder by the immersion method, using

The *microcline* is finely cross-hatched. The feldspars and the *quartz* form the aplitic mass in which scales of *muscovite*, *biotite*, and *calcite* are scattered.

In the muscovite, $\beta_D = 1.615 \pm 0.003$, and in the biotite $\beta_D = \gamma_D = 1.650 \pm 0.003$. Unfortunately there are not yet sufficient data to establish the composition of the micas from the refractive indices. The biotite probably has about 80 per cent of the iron compound.[1]

The mode of this rock was calculated with the following result:

Quartz	27.7	Biotite	4.0
Albite	38.2	Calcite	2.0
Anorthite	3.2	Apatite	0.2
Microcline	15.0		
Muscovite	10.0		100.3

This is a rock in which calcite occurs as a primary mineral. Emerson remarks (*op. cit.*, p. 153): "Because of its proximity to the Coles Brook limestone it contains microscopic grains of calcite."

All the analyses of the Becket gneiss show an ordinary granitic composition with about equal amounts of potash and soda and very little lime. A study of thin sections of a number of specimens proved this to be a general rule. Some of them, however, do not contain any potash feldspar, but all are rich in mica.

---

a monochromatic illuminator and Dr. Merwin's dispersion diagram for the set of liquids (see E. Posnjak and H. E. Merwin, *Jour. Amer. Chem. Soc.*, Oct., 1922). In the case of feldspars, where birefringence is low and dispersion sufficiently known, this method offers the advantage that all the indices of refraction can be determined with only one liquid. In the actual work it was found convenient either to determine β only, or to seek grains showing the highest birefringence and determine, in three of four grains, α' and γ', taking the lowest and highest values found. The composition was then located on the curves published by F. E. Wright, *Am. Jour. Sci.* (4) (1913), pp. 36, 540. The latter is the quickest way and sufficiently accurate to give the composition of the plagioclase within the limits of 2 or 3 mol. per cent.

[1] The lowest indices of refraction in biotites recorded are those in yellowish brown biotite from Vesuvius, $\alpha_D = 1.5412$; $\gamma_D = 1.5745$, and the highest those in black biotite from Somma: $\alpha_D = 1.5795$; $\gamma_D = 1.638(3)$. The highest value of γ is much lower than that often found during this work. The maximum value, found in a biotite from biotite gneiss, railroad line between Becket and Washington, was $\gamma_D = 1.660 \pm 0.003$. Taking this value and $\gamma_D = 1.574$ as limits a very rough approximate estimation of the composition of biotites may be obtained graphically.

LIMESTONE AND SKARN[1]

Emerson characterizes the Coles Brook limestone in the following words:[2] "The Coles Brook is a coarse, highly crystalline, magnesian limestone, locally white and pure, generally graphitic and greatly changed to a mass of silicates—chondrodite, wollastonite,[3] wernerite, hypersthene, pyroxene, amphibole, titanite, adularia, pericline, and others. . . . ."

In the following are given the writer's observations on the limestones in western Massachusetts.

About $\frac{1}{2}$ mile east of *Benson Pond*, 1 mile east of Washington Station, a band of limestone, a few meters broad, occurs in the gneiss. It is rendered impure by the presence of greenish white mica, reddish brown chondrodite, and clear brown titanite.

The *mica* is nearly, though not quite, uniaxial and has $\beta_D = \gamma_D = 1.576 \pm 0.002$. It is a magnesian mica, very poor in iron, but probably not phlogopite.

The *chondrodite* is notably pleochroic, α and β reddish brown, γ pale brown. $\dot{\alpha} \wedge \beta = 31° \cdot \alpha_D = 1.621 \pm 0.003$; $\beta_D = 1.632 \pm 0.001$; $\gamma_D = 1.655 \pm 0.003$.

This limestone is a calcite rock and contains no dolomite.

In apparent connection with the limestone, on its continuation along the strike, were found many inclusions of clinopyroxene skarn in an aplitic variety of the gneiss which contains varying amounts of the same kind of pyroxene (Fig. 1) as the skarn.

Many of the inclusions are sharply defined, coarsely crystalline masses of grayish green clinopyroxene, although narrow veinlets always protrude into them from the aplite. These veinlets always contain minute grains of red *grossularite-andradite* which is also concentrated within a narrow zone around the inclusions. It is appar-

[1] "Skarn.—An old Swedish mining term for the silicate gangue (amphibole, pyroxene, garnet, etc.) of certain iron ore and sulphide deposits of Archaean age, particularly those which have replaced limestone and dolomite. The term is used in this sense by Fennoscandian geologists, but it has been extended to cover analogous products of contact metamorphism in younger formations." A. Holmes, *The Nomenclature of Petrology* (London, 1920), p. 211.

[2] B. K. Emerson, *U.S. Geol. Surv., Bull. 597,* p. 21.

[3] This statement about wollastonite does not occur in the other more detailed reports and may be erroneous.

ently heterogeneous, its index of refraction (n_D) varying from 1.775 ± 0.005 to 1.801 ± 0.005. This means a variation in composition from 25 to 43 wt. per cent andradite in the mixcrystals, supposing them to contain only andradite and grossularite.[1]

The *clinopyroxene* has $\beta_D = 1.696 \pm 0.001$ and the angle $\dot{c} \wedge \gamma = 43°$. Hence its composition should be $Di_{69}He_{31}$.[2]

FIG. 1.—Inclusions of clinopyroxene skarn in aplitic gneiss. E. of Benson Pond, Washington, Massachusetts. Eight-ninths natural size.

Together with the garnet in the veinlets there is *quartz*, *microcline* and *plagioclase*. The latter, having $\alpha'_D = 1.532$ and $\gamma'_D = 1.540$, has the composition about Ab_{91}.

[1] W. E. Ford, *Amer. Jour. Sci.* (4), Vol. XL (1915), pp. 33–49.

[2] The determinations of pyroxenes of the diopside-hedenbergite series by means of the indices of refraction were made with a diagram (Fig. 2) based on the optical data given by Wülfing (H. Rosenbusch and E. A. Wülfing, *Mikroskopische Physiographie*, I, 2, p. 203) and on the analyses of the same pyroxenes published by G. Flink (*Zs. Kr.*, Vol. II (1895), p. 585). Although the analyses are antiquated, these data no doubt give a correct idea of the relations between composition and optical properties of clinopyroxenes containing little or no sesquioxydes. Drs. H. E. Merwin and H. S. Washington are at present carrying on an investigation of all the pyroxenes and they no doubt will give a better diagram of this series. As their work is not far advanced and it may be some years before their results are published, we give here the diagram based on Flink's and Wülfing's data.

Small amounts of deep green *hornblende* ($\beta_D = 1.677 \pm 0.002$) are associated with the pyroxene.

Considerable quantities of *epidote* occur near the margins of the skarn inclusions. Its refringence varies within single grains, being lowest in the centers.

On the hillside just *north of Becket Station* there is exposed a vertical layer of limestone, surrounded by clinopyroxene gneiss.

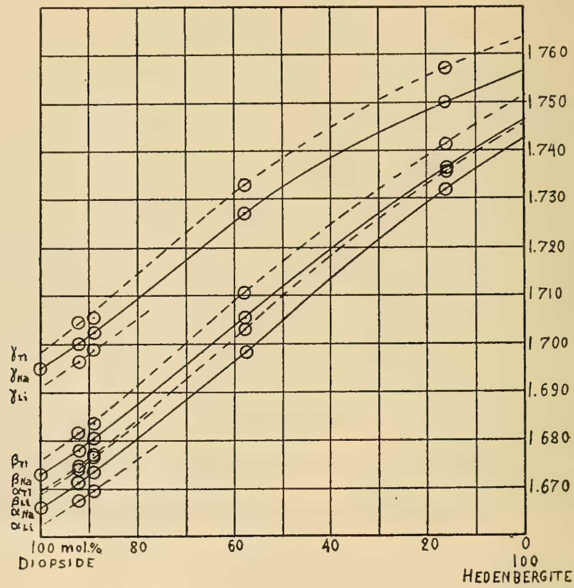

FIG. 2.—Variation of the indices of refraction in the diopside-hedenbergite series. The small amounts of ferric oxide present have been calculated as ferrous oxide. After E. A. Wülfing and G. Flink. The indices of pure diopside were determined by H. E. Merwin.

A specimen of the limestone was found to contain, besides calcite, much quartz and clinopyroxene of the composition $Di_{67}He_{33}$, having $\beta_D = 1.698 \pm 0.002$.

One of those narrow valleys within the Becket gneiss area that are underlain by the Coles Brook limestone is *Goose Pond Brook Valley*. It joins the broader East Lee Valley near East Lee. Limestone occurs in small outcrops in the bed of the brook, and little can be said about its mode of occurrence, but it seems to be in immediate contact with the clinopyroxene gneiss that is exposed close by.

Among the specimens collected some were very rich in *calcite* with only sparing amounts of *dolomite* crystals, the latter being easily recognizable from their higher indices of refraction ($\omega_D = 1.683 - 1.684$; the calcite always was found to have $\omega_D = 1.660$).

Other specimens collected contain pale brown *biotite*, having $\beta_D = \gamma_D = 1.599 - 1.600$, and *quartz*, as rounded grains.

A specimen from the wider *East Lee Valley*, where the Coles Brook limestone occurs as a larger mass, represents a dolomite-rock containing rounded grains of *quartz* and *microcline*, and minute crystals of *pyrite* and scales of brownish, nearly uniaxial *mica* with $\beta_D = \gamma_D = 1.599 \pm 0.002$.

It may be mentioned that these characters are the same as those in the most common types of the Stockbridge limestone in the Housatonic Valley. Analyses[1] of the Stockbridge indicate that there are all variations between dolomite-rocks and calcite-rocks represented. We collected specimens of this limestone from Glendale quarry. It is a dolomite-rock, with much fine scaly brownish *mica* ($\beta_D = \gamma_D = 1.584 \pm 0.002$) and brown *tourmaline* ($\omega_D = 1.639 \pm 0.001$).

BANDED GNEISS NEAR THE LIMESTONE AND THE VARIATION OF ITS MINERAL COMPOSITION

The gneiss, near the vertical, or almost vertical, layers of limestone, always shows a banded structure parallel to the strike of the limestone. At the immediate contacts it is clinopyroxene gneiss. Farther away there are various bands, some containing hornblende, and others with almandite, biotite or magnetite as the principal mafic minerals, and among them are bands of the clinopyroxene gneiss also.

The individual bands may be homogeneous or banded in detail (Fig. 3), due to the unequal distribution of the minerals. The breadth of homogeneous bands varies from less than one meter to a hundred meters. Among the pyroxene-bearing bands, however, none was found thicker than some ten meters.

A common feature of all the varieties of gneiss, of widely different mineral composition, is the presence of very albitic plagioclase (mostly about 90 per cent Ab) and epidote whose

[1] B. K. Emerson, *U.S. Geol. Surv.*, *Bull. 159* (1899), pp. 87 and 99.

amount increases with the quantity of the femic compounds, a fact indicating that it is a substitute for anorthite. The epidote occurs as clear, individual crystals, often intergrown with quartz in the myrmekite fashion.

Another feature significant in connection with the conditions of formation of these banded gneisses is the absence of perthitic threads of plagioclase in the microcline, which is clear and finely cross-hatched. The texture, on the whole, is aplitic, and all the main minerals are equally xenomorphic.

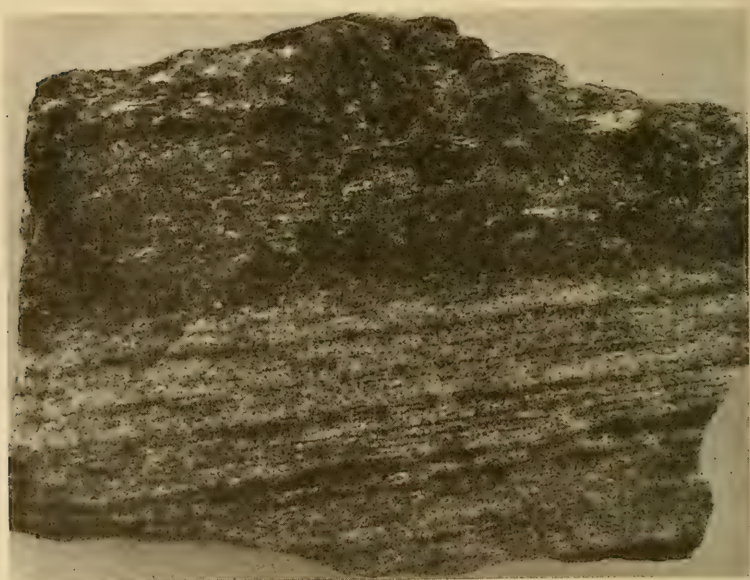

FIG. 3.—Banded clinopyroxene gneiss. W. of Benson Pond, Washington, Massachusetts. Eight-ninths natural size.

Emerson (*op. cit.*, p. 153) published an analysis of clinopyroxene gneiss, called by him "titanite-pyroxene diorite aplite," from "east of C. Conwell's place, South Peru, Mass." The analysis, made by W. T. Schaller, is quoted below (p. 275).

I have found these clinopyroxene-bearing rocks to be exceedingly variable in composition, and the analysis has happened to be made on a rather exceptional type. Most specimens collected by us from the same tract and, also, one collected by Professor Emerson from the Peru line, "the same ledge as the rock analyzed" (*U.S.*

Geol. Surv., P.R.C. 1715), contain considerable amounts of quartz and microcline. They therefore must have a higher percentage of silica and potash. Assuming the plagioclase to contain 90 mol. per cent Ab and a notable quantity of epidote to be present, the mode given in the table was calculated from the rock analysis by the writer. The pyroxene was computed as a diopside-hedenbergite with 10 per cent (Mg, Fe)SiO_3 and 4 per cent Al_2O_3.

The clinopyroxene, in the specimen from the Peru line, is pale green without any notable pleochroism. It was found to have $\alpha_D = 1.695 \pm 0.002$, $\beta_D = 1.706 \pm 0.002$; $\gamma_D = 1.724 \pm 0.002$, and should

	Per Cent	Mol.	Mode			
SiO_2	60.44	1.007	Albite		60.26	
Al_2O_3	16.26	159	Anorthite		7.51	
Fe_2O_3	0.07	.....	Potash feldspar		2.78	
FeO	3.52	49	Pyroxene	$CaSiO_3$	8.82	20.49
MgO	1.75	44		$MgSiO_3$	4.40	
CaO	7.86	140		$FeSiO_3$	6.47	
Na_2O	7.13	115		Al_2O_3	0.80	
K_2O	0.44	5	Epidote		1.93	
			Quartz		2.16	
H_2O+	0.38	.....	Titanite		3.14	
H_2O-	0.29	.....	Apatite		1.34	
TiO_2	1.33	16	Zircon		0.09	
P_2O_5	0.58	4	Pyrite		0.10	
MnO	0.06	1			99.80	
ZrO_2	0.06	.....				
FeS_2	0.10	.....				
	100.27					

therefore contain 60 mol. per cent diopside and 40 per cent hedenbergite, or $Di_{60}He_{40}$, while calculation from the analysis gave $Di_{48}He_{42}$. Thus the specimen analyzed contained a pyroxene richer in iron. As we shall see, the composition of the clinopyroxene in these gneisses varies markedly from place to place.

The epidote is highly birefracting and has $\beta_D = 1.750 \pm 0.003$, nearly the same value as that found in the epidote from Knappenvand, Sulzbachtal,[1] which contains 33 per cent of the ferric epidote (16 per cent Fe_2O_3) and has $\beta_D = 1.7540$.

[1] M. Goldschlag, *Tscherm. Min. Petr. Mitt.*, Vol. XXXVIII (1917), p. 23. The data given in this study, the most careful one ever carried out on the epidote group, are not yet consistent enough to allow the determination of the amounts of the aluminous and the ferric compounds in epidotes more accurately than with a possible error of ±5 per cent.

The prominent characters of the mineral composition of the various kind of gneiss are stated in the following. The mineral constituents of each rock are named in the approximate order of abundance. The refractive indices were determined, if not stated otherwise, with a maximum error of ± 0.003 in biotite and hornblende and epidote, and ± 0.002 in plagioclase and pyroxene. The composition of the minerals is given in terms of mol. per cent, stating: in plagioclases the percentage of anorthite (An), in clinopyroxenes (diopside-hedenbergite) the percentage of hedenbergite (He), in hornblende the total Fe as a percentage of Fe+Mg,[1] and in the biotites and epidotes (very roughly) the percentages of their iron compounds.

Aplitic clinopyroxene gneiss around the inclusions of skarn. Mainly microcline, subordinate plagioclase (An_8), quartz, clinopyroxene ($\beta_D = 1.705$, $\gamma_D = 1.727$, He_{42}), epidote, variable, sometimes very poor in Fe,[2] calcite.

Banded clinopyroxene gneiss (Fig. 3) in biotite gneiss, W. of Benson Pond. Microcline, quartz, plagioclase ($\alpha'_D < 1.536$; $\gamma'_D = 1.544$; An_{15}), clinopyroxene (He_{69}),[3] titanite, epidote.

[1] Calculated from the diagrams given by W. E. Ford, *Amer. Jour. Sci.*, Vol. XXXVII (1914), p. 185.

[2] I measured in one case for different wave-lengths, with a maximum error ± 0.001:

	α	β	γ
Tl..........	1.703	....	1.707
D...........	1.698	1.700	1.702
C...........	1.693	....	1.697

These values are lower than any given in the literature (cf. M. Goldschlag, *loc. cit.*). This mineral is, however, monoclinic, and not a zoisite. $2V = 90°$ appr.

[3] In it were determined, with a maximum error ± 0.001:

	α	β	γ
Tl..........	1.724	1.7305	1.748
D...........	1.720	1.726	1.743
C...........	1.716	1.721	1.738

The birefringence suggested that this clinopyroxene is richer in hedenbergite than any other found in this tract. Its refractive indices for various wave-lengths are in fair agreement with those of $Di_{31}He_{69}$ as shown on the diagram. Its extinction

"Pyroxene-titanite aplite" from the Peru line. Plagioclase ($\beta_D = 1.536$; $\alpha'_D = 1.531$; $\gamma'_D = 1.542$; An_{10}), microcline, quartz, hornblende ($\beta_D = 1.676$; Fe_{51}), clinopyroxene ($\alpha_D = 1.695$; $\beta_D = 1.706$; $\gamma_D = 1.724$; He_{40}), titanite, biotite ($\beta_D = \gamma_D = 1.647$; 80 per cent Fe-comp.), epidote ($\beta_D = 1.750$; 33 per cent Fe-comp.), apatite.

Intrusive layer in limestone N. of Becket Station. Quartz, plagioclase (An_{11}), microcline, clinopyroxene ($\beta_D = 1.700$; He_{35}), hornblende ($\beta_D = 1.680$; Fe_{53}), grossularite-andradite ($n_D = 1.80$; 40 wt. per cent andradite), calcite, epidote.

Band in the gneiss, railroad cut W. of Becket Station. Quartz, microcline, clinopyroxene (colorless; $\alpha_D = 1.685$; $\beta_D = 1.690$; $\gamma_D = 1.714$; $\gamma \wedge \dot{c} = 41°$; He_{25}), actinolite (pale green; $\beta_D = 1.638$; Fe_{19}), graphite, calcite, titanite.

Clinopyroxene gneiss near limestone in the valley of Goose Pond Brook. Clinopyroxene (colorless, $\beta_D = 1.681 \pm 0.001$; He_{11}), amphibole ($\beta_D = 1.633 \pm 0.002$; Fe_{14}), quartz, microcline, plagioclase ($\beta_D = 1.534$; An_7), epidote ($\beta_D = 1.730$; 18 per cent Fe-comp. or 9 wt. per cent Fe_2O_3). Occasional scapolite ($\omega_D = 1.572 \pm 0.001$; $\epsilon_D = 1.547 \pm 0.001$; about $Me_{50}Ma_{50}$) and black tourmaline.

Dark band in the gneiss South of Benson Pond. Clinopyroxene ($\beta_D = 1.695$; He_{31}), hornblende ($\alpha_D = 1.672$; $\beta_D = 1.685$; $\gamma_D = 1.695$; Fe_{59}), plagioclase (zoned, An_{17} to An_7), quartz, microcline, titanite, biotite ($\beta_D = \gamma_D = 1.635$; about 65 per cent Fe-comp.).

Dark band N. of Benson Pond. Plagioclase (zoned, An_{23} to An_{16}), hornblende ($\beta_D = 1.660$; Fe_{36}), biotite ($\beta_D = \gamma_D$ 1.642; 75 per cent Fe-comp.), quartz, epidote, titanite, apatite.

Dark band in the gneiss N. of Becket Station. Biotite ($\beta_D = \gamma_D = 1.620$; 50 per cent Fe-comp.), hornblende ($\beta_D = 1.650$; Fe_{29}), plagioclase ($\beta_D = 1.536$; $\alpha'_D = 1.532$; $\gamma'_D = 1.541$; An_{10}), microcline, quartz, epidote. The quantity of epidote is considerable.

"Lee quartz diorite" from west end of Goose Pond. Plagioclase (zoned, An_{32} to An_{29}), hornblende ($\beta = 1.665$ appr.; Fe_{40}), cum-

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angle $\gamma \wedge \dot{c}$ however, does not accord with the series, being 58° instead of 46° 20′. Probably this clinopyroxene contains a certain amount of aegirite, although its very faint pleochroism (α = pure green, γ = brownish) indicates that the amount may be small.—In another specimen was found a clinopyroxene He_{60}($\beta_D = 1.721$).

mingtonite, forming the inner parts of the aggregates of amphibole (positive, 2V large, $\beta_D = 1.650$; about 40 mol. per cent $FeSiO_3$), quartz, ilmenite, apatite, zircon.

Almandite amphibolite, band in gneiss, roadside W. of Benson Pond. Plagioclase ($\alpha'_D = 1.540$; $\gamma'_D = 1.548$; An_{25}), almandite ($n_D = 1.806 \pm 0.001$; probable composition[1] 70 mol. per cent almandite, 15 mol. per cent pyrope and 15 mol. per cent grossularite), hornblende ($\beta_D = 1.665$; Fe_{40}) microcline, biotite ($\beta = \gamma = 1.648$; about 80 per cent Fe-compound), ilmenite, apatite.

Biotite gneiss, railroad line between Washington and Becket stations. Quartz, plagioclase (An_9) microcline, biotite ($\beta_D = \gamma_D = 1.660$, chiefly iron compound), hornblende ($\alpha_D = 1.697$; $\beta_D = 1.708$; $\gamma_D = 1.709$;[2] $2V\alpha$ small Fe_{90}), magnetite, epidote ($\alpha_D = 1.741 \pm 0.002$; $\beta_D = 1.760 \pm 0.005$; $2V = 75°$ appr.; about 35 mol. per cent iron comp.).

THE MG:FE PROPORTION IN THE VARIOUS BANDS OF THE GNEISS AND IN ITS DIFFERENT MAFIC MINERALS

A comparison of the Fe:Mg proportions, as determined from the refractive indices of the pyroxenes, amphiboles, and biotites in the various kinds of gneiss, shows at once that they are controlled by definite laws. For the sake of convenience, the values of the atomic portions of Fe as a percentage of Fe+Mg (briefly called the Fe-quotient) are tabulated (p. 279).

In this table, the rocks are arranged in the order of decreasing Fe-quotient in their amphiboles and pyroxenes. Now, comparing this order with the statements of the approximate quantitative proportions of the minerals given in the preceding chapter, we find at once that it is, also, at least nearly the order of increasing basicity or decreasing acidity, excepting, however, the two last-named examples of clinopyroxene gneiss. Their case will be discussed below.

[1] P. Eskola, "On the Eclogites of Norway," *Videnskapsselsk. Skri. Mat.-naturv. Kl.* I, No. 8 (1922), p. 9.

[2] The indices match the highest values represented in the amphiboles studied by Ford (*Amer. Jour. Sci.*, Vol. XXXVII [1914], p. 181), i.e., those of the hornblende from Cornwall, Orange County, New York, which has a mean index 1.71 and contains 23.35 per cent FeO and 7.41 per cent Fe_2O_3 against 1.90 per cent MgO and 12.10 per cent Al_2O_3.

In other words: the larger the quantity of the mafic minerals, the smaller is their Fe-quotient. In the most acid types of gneiss, rich in quartz, we find biotite and hornblende, and often clinopyroxene also, extremely rich in iron. In the mafic minerals of the "dark bands" the amount of iron in proportion to magnesia is much less.

At the same time as the Fe-quotient decreases, the amount of anorthite in the plagioclases increases. This relation is somewhat obscured by the epidote, a substitute for the anorthite.

Rocks	100 Fe:(Fe+Mg) in			Other Minerals
	Clinopyroxenes	Hornblendes	Biotites	
Biotite gneiss, railroad at Becket Station	......	90	95(?)	....
Clinopyroxene gneiss, W. of Benson Pond	69	......	......	....
Clinopyroxene gneiss, "the Peru line"	40	51	80	....
Clinopyroxene gneiss, Becket Station	35	53	......	Grossularite-andradite, 40 per cent andr.
Dark band in gneiss, S. of Benson Pond	31	59	65	....
Almandite amphibolite, W. of Benson Pond	......	40	80	Garnet with 70 per cent almandite
Dark band in gneiss, N. of Benson Pond	......	36	75	....
Dark band in gneiss, Becket Station	......	29	50	....
Clinopyroxene gneiss, railroad between Becket and Washington	25	19	......	....
Clinopyroxene gneiss, Goose Pond Brook	11	14	......	....

The percentage of the iron compound in the epidotes does not show quite regular relations with that in the mafic minerals. This is probably connected with the later origin of the epidote.

This correspondence between the Fe:Mg ratio and the relative proportion of salic and femic minerals is a special case of what is inherent in any cognate series of igneous rocks which have been derived from a common magma by the processes known as magmatic differentiation. Its occurrence in the banded gneiss proves that the band structure is in itself a product of differentiation. In other words, the "dark bands" are those in which the minerals containing solid solutions are richest in the highest melting compounds or, more exactly, compounds least soluble in the residual magmas. The mafic minerals of these most "basic" members of

the series are pyroxene and amphibole. With increasing acidity biotite and muscovite appear successively.

The occurrence and composition of clinopyroxene does not always follow this rule, and for a very obvious reason: its occurrence is due to the assimilation of limestone, which is dolomitic, and low in iron. Therefore, when it reacts with the highly siliceous gneiss magma, there is formed pyroxene and, also, hornblende and biotite, low in iron, provided differentiation by crystallization has not changed the composition of the magma after assimilation. In many cases a differentiation happened, however, and therefore the mafic minerals of very acid clinopyroxene gneisses not immediately connected with limestone usually show a high Fe-quotient.

Another interesting question is this: How are magnesia and the iron oxides distributed between the different ferromagnesian minerals?

As appears from the table on page 279, there are definite relations between the pyroxenes, amphiboles, and biotites, in this respect. Biotite is regularly the richest in iron and clinopyroxene the poorest. The figures do not show any constant relations between the Fe-quotients, however. This is only what may be expected. From theoretical considerations the distribution of elements in different isomorphous series in a rock is evidently a very complicated process, depending upon the composition of the solutions from which the minerals crystallized and, also, on the temperature and pressure conditions during crystallization. In rocks of identical bulk composition these relations may be expected to vary with the physical conditions. It may be hoped that, when once they are better understood, we shall be able to draw from them certain conclusions as to the conditions under which the rocks originated.

The present writer has formerly studied the almandite-pyrope garnets of different rocks from this standpoint and has arrived at the conclusion that, in rocks of similar composition, those formed under highest pressures have garnets richest in the magnesia compound.[1]

[1] P. Eskola, "The Mineral Facies of Rocks," *Norsk geologisk Tidskrift*, Vol. VI (1920), p. 172.

These brief statements are given here in order to call the petrologist's attention to these relations, formerly very little studied.

VARIATION OF MINERAL PARAGENESIS IN METAMORPHIC LIMESTONE

Sedimentary limestones generally consist of carbonates of calcium and magnesium, and of silica, in the form of quartz. Very often they also bear clayey materials, containing alumina, iron oxides, potash, etc. When such material is brought from surface conditions down to deeper levels where a higher temperature prevails there will occur reactions of the general type:

$$RCO_3+SiO_2=RSiO_3+CO_2.$$

The temperature limit above which the right-hand side of the foregoing equation represents the stable combination, or the transformation point of the chemical system, is raised with pressure. For the reaction $CaCO_3+SiO_2=CaSiO_3+CO_2$, V. M. Goldschmidt calculated the approximate equilibrium curve on the basis of Nernst's affinity theorem.[1] According to this curve, the equilibrium temperature increases rapidly with the pressure, being 850° at 300 atm. Thereafter the rise of the equilibrium temperature with pressure should be nearly linear and so slow that as much as 15,000 atm. would be needed at 950°. Considering rocks of neighboring occurrences which have originated under similar pressures but at different temperatures, as is often the case at the contacts of igneous masses, the limestone indicates what parts of it have been heated above the reaction point. If the pressure be known, the temperature may be estimated in degrees. In the case of rocks whose metamorphism has taken place under pressures of more than 3,000 atm., or at depths of more than 10 kilometers, the equilibrium temperature is but slightly variable with pressure, and the mineral composition of silica-bearing limestones is mainly an indicator of temperature, or the limestone may be used as a *geologic thermometer*.

This curve is not claimed to be more than approximate. Experimental investigation may give considerably different results.

[1] V. M. Goldschmidt, "Die Gesetze der Gesteinsmetamorphose," *Vid. selsk. Skr. Mat.-naturv. Kl.*, No. 22 (1912).

Certain facts known at present would seem to indicate that the curve may lie at somewhat lower temperatures. Its general character, however, agrees well with petrological experience and is not likely to be subject to any great changes.

From the standpoint of the phase-rule, a mixture of calcium carbonate and silica is a three-component system and therefore can have a maximum of three phases in coexistence under variable pressure and temperature conditions, that is, in a divariant system. Below the transformation curve the possible three-phase combinations are either silica, calcite, and carbon dioxide or silica, calcite, and wollastonite. Above the curve we may have either wollastonite, carbon dioxide, and calcite or wollastonite, carbon dioxide, and quartz (or any other form of silica).

Thus wollastonite may be stable and even be formed at temperatures below the transformation curve, but only if silica meets lime in other form than carbonate and no free carbon dioxide is present. The occurrence of wollastonite, therefore, is not in itself a sufficient evidence that the rock had been heated above the transformation temperature. On the other hand the occurrence of both quartz and calcite proves conclusively that it never has.

The temperature of transformation may be considerably depressed if the partial pressure of carbon dioxide is kept low as a result of its continual removal, e.g., by circulating solutions. This case may occur in the formation of metasomatic ore deposits, and in fissure veins. The conditions are here complicated also because the addition of substances and formation of minerals may have continued at different temperatures. As a matter of fact, observation usually indicates a definite sequence of formation of minerals in such deposits.

While, then, many complications are to be expected where circulating solutions have been prominent agents, we may still use limestone as a geologic thermometer with considerable confidence in those cases in which quartz or the silicates occur evenly distributed as true rock constituents.

As we are concerned, in natural rocks, with calcium and magnesium carbonates, the resulting silicates will be those of calcium and magnesium, or double compounds of both. It is to be expected

that magnesium-bearing carbonates will react with the silica at lower temperatures than calcium carbonate. Each silicate to be formed may have its own equilibrium curve.

This assumption has been very strongly supported by petrological investigations which I have carried out in the pre-Cambrian limestone of Finland.[1] In the southeastern part of the pre-Cambrian area of Fennoscandia there are extensive formations all of whose characters point toward metamorphism at low temperatures. In the limestones of this area, quartz occurs together with dolomite, and fine scaly micaceous minerals (biotites rich in magnesia) are usually the only silicates. Sometimes epidote occurs, a fact indicating that this hydrated calcium aluminium silicate also belongs to the low temperature minerals.

Northwest of this low temperature area there is a broad zone within which the limestones contain, besides mica, amphiboles of the tremolite-actinolite series, but no other silicates. Going farther northwest diopside-hedenbergite is added to the list of minerals of the metamorphic limestones, together with many others, such as scapolite, vesuvianite, and grossularite-andradite. Finally we find, as local developments near the contacts of igneous masses, but never in regional distribution, wollastonite limestone, and in this most of the other silicates may occur also. This mode of occurrence clearly indicates that wollastonite, among the lime-bearing silicates, requires the highest temperature to form.

We may thus discriminate the following four paragenetic types of limestones:

1. **Quartz limestone,** in which quartz is coexistent with the dolomite.

2. **Tremolite limestone.** Tremolite is usually present; quartz occurs in calcite-rock, but is not coexistent with dolomite.

3. **Diopside limestone.** Diopside is usually present, quartz occurs together with calcite but not with dolomite.

4. **Wollastonite limestone.** Wollastonite is present, provided the rock contains silica in excess of the amount needed to form the

[1] Pentti Eskola, Victor Hackman, Aarne Laitakari ja W. W. Wilkman, Suomen kalkkikivi. With an English summary by P. E., "Limestones in Finland," *Suomen Geologinen Toimisto, Geoteknisiä Tiedonantoja,* No. 21 (1919).

magnesium-bearing silicates. Quartz and calcite do not occur in contact with each other. Instead either of the combinations calcite-wollastonite or wollastonite-quartz occurs.

Actual rocks have commonly been found in fair accordance with these rules of association. As was pointed out above, wollastonite is in itself stable below the transformation temperature of calcite-silica, if there is no free carbon dioxide present. In the same way diopside and tremolite are stable below those temperatures where they may be formed from the carbonates and silica, again provided that there is no carbon dioxide present. Now there actually is no free carbon dioxide after the formation of the silicates, as it is carried away either as gas or in solutions. Therefore, although the reactions are reversible, they are not reversed during the period of gradual cooling when the rocks are brought up toward the earth's surface through the process of denudation. This fact, of course, adds very much to the usefulness of metamorphic limestone as a geologic thermometer. We always read the highest temperature to which it has ever been exposed. It is a maximum thermometer.

The formation of different minerals under different conditions in limestones presents a special case of the more general rules of adjustment of mineral composition in response to the conditions existing. The writer has proposed the term *mineral facies*[1] to designate a group of rocks which have originated under conditions so similar that a definite chemical composition has resulted in the same set of minerals. Applying this principle to various kinds of rocks, we arrive at a natural rock classification in which main divisions are the groups called mineral facies.

The four paragenetic types of limestone may be paralleled with the facies system of the silicate rocks in the following way:

Under conditions similar to those that give rise to quartz limestones, rocks having the bulk composition of gabbros have been metamorphosed into chlorite-epidote-albite rocks. This mineral facies has been called the *greenschist facies*.

[1] P. Eskola, "The Mineral Facies of Rocks," *Norsk geologisk tidskrift*, Vol. VI (1920), pp. 143–94.

Tremolite limestones correspond with transitional forms between the greenschist facies and another facies called the *amphibolite facies*, because a rock of gabbroid composition whose minerals have formed under the conditions of this facies, appears as a plagioclase-hornblende rock, an amphibolite.

The diopside limestones, so far as known at present, also belong to the amphibolite facies, and even some of the wollastonite limestones belong here, but the last named cover a wide range of temperature and pressure conditions corresponding to several kinds of mineral development in the silicate rocks, and a gabbroid material may give any one of the mineral combinations: plagioclase and clinoenstatite-diopside solid solutions (provisionally referred to as the *sanidinite facies*) or plagioclase, diopside, and hypersthene (*hornfels facies*), or diopside-jadeite solid solutions and pyrope-almandite solid solutions (*eclogite facies*).

Metamorphic limestone as a geologic thermometer can be calibrated against the transformation points of the silica minerals. The fact that quartz, and not tridymite, occurs even with wollastonite, would seem to indicate that the wollastonite-curve passes below the transformation point quartz-tridymite. This is, according to Fenner,[1] 870°, but it must rise somewhat with pressure. As to the transformation point α-β-quartz at 575°, it has been established that crystals of quartz in a diopside limestone from Parainen in southern Finland, have been originally α-quartz,[2] while the quartz-dolomite rocks of eastern Finland contain clear crystals of quartz which is apparently primary β-quartz. More observations on this subject are desirable.

It is to be hoped that the temperature-pressure curves for the different silicate-carbonate equilibria may be determined exactly by experiment, in the near future.

In the contact zones of the Becket gneiss in western Massachusetts three of these paragenetic types of limestone occur, namely: quartz limestone, tremolite limestone, and diopside limestone. The temperature was probably nowhere high enough to

[1] C. N. Fenner, *Amer. Jour. Sci.*, Vol. XXXVI (1913), p. 331.

[2] A. Laitakari, *Bull. Com. géol. Finl.*, 54 (1920), p. 40.

allow wollastonite to be formed,[1] and quartz is generally found in contact with calcite.

Quartz limestone is the most widely distributed type in western Massachusetts. Most of the Stockbridge limestone belongs to it and, also, much of the Coles Brook limestone. Such were the specimens from Goose Pond Creek and East Lee described above (p. 272). They consist of dolomite and quartz, sometimes with microcline.

During the excursions we did not happen to meet with any typical tremolite limestone, but it is apparent from Emerson's descriptions that it is a common type, in the Stockbridge as well as in the Coles Brook.[2]

Tremolite limestone is noted "south of Becket" (Emerson, *U.S. Geol. Surv., Mon. 29*, p. 27), and from Lee (*U.S. Geol. Surv., Bull. 159*, p. 84). Tremolite but no pyroxene in limestone is mentioned in the "Mineral Lexicon of Eastern Berkshire Co." (last-cited volume) from Windsor, Monterey, and the Cobble in Tyringham.

Through the courtesy of Mr. E. V. Shannon the writer was able to study specimens from the collections of the United States National Museum of tremolite limestone (Stockbridge) from Lee, Massachusetts, and from Canaan, Connecticut, near the Massachusetts line. The rock from both localities was found to consist

[1] Cf. footnote 1 on p. 285.

[2] It might be objected that it is not justifiable to regard the Stockbridge and the Coles Brook limestones as equivalents in their metamorphic development. For, if the former is Cambrian, while the latter, with the Becket gneiss intrusive in it, is pre-Cambrian, the Stockbridge cannot have been influenced by the heat of this intrusion which undoubtedly has changed the Coles Brook limestone. Now the plain fact is that the same three types of mineral paragenesis occur in both of them. The Coles Brook limestone, when belonging to the quartz type, is exactly like the most common type of Stockbridge limestone. The occurrence of tourmaline in the latter, recorded above, points to the vicinity of magmas. Emerson knew this, and he assumed that there may be post-Cambrian igneous masses not quite exposed on the present land surface. If this is true, then the earlier and the later intrusions have taken place during very similar physical conditions. It seems worth while, in future investigation of the geology of western Massachusetts, to consider the possibility that the Becket gneiss is of post-Cambrian origin, and the Coles Brook limestone only the margin of the Stockbridge. In fact our observations at the eastern as well as at the western contact of the Becket batholith seemed to indicate that this is the case.

of dolomite, calcite, and tremolite, with some brown mica ($\beta_D = \gamma_D = 1.582 \pm 0.003$), but no quartz. It thus proves to represent a true equilibrium under those temperature-pressure conditions which give rise to tremolite limestone.

Diopside limestone occurs so commonly that it is not necessary to name more than a few localities, as examples. Emerson[1] describes pyroxene- and actinolite-bearing limestone from Hinsdale and East Lee, both being Coles Brook limestone. His "Mineral Lexicon of Eastern Berkshire Co." (*op. cit.*) mentions pyroxene from the Stockbridge limestone from New Marlboro and several places in Tyringham.

The writer studied diopside limestone from Becket Station, a combination of calcite, quartz and diopside. It is a rock of the diopside limestone type. All the dolomite has been exhausted in the formation of diopside, while some quartz has been left.

Theoretical reasoning leads to the conclusion that the quartz-carbonate rocks, when they are metamorphosed under medium temperature conditions, corresponding to the tremolite and diopside limestone types, are likely to become poorer in dolomite. This must finally cause a dedolomitization of the limestone.

The silica need not occur within the limestones themselves, but may react at the boundaries. In small bodies of limestone bounded by highly siliceous rocks, and especially when submerged in magmas of such acid rocks, this may be expected to give rise to a perfect dedolomitization. So far as the writer's experience goes, small bodies of limestone inclosed in granites or gneisses really consist of calcite-rock, while magnesium-bearing silicates occur at their contacts. This rule was confirmed in the Massachusetts localities studied, near Benson Pond and near Becket Station.

ASSIMILATION OF LIMESTONE BY GRANITIC AND PEGMATITIC MAGMAS

The writer believes that the mode of occurrence of the clino-pyroxene gneiss around and near the occurrences of limestone included in the gneiss is in itself sufficient evidence that the gneiss has received its excessive amount of lime through assimilation of the limestone.

[1] *U.S. Geol. Surv., Bull. 159*, pp. 32 and 51.

We have found that the clinopyroxene gneiss has, in the majority of cases, a composition that is nearly the same as that of the ordinary Becket gneiss of the surrounding area, excepting that it has a higher amount of lime. A bulk composition may therefore be computed from the analysis of the gneiss quoted above (p. 268), by allotting CaO enough to form anorthite with all the excess alumina (actually present in the micas), to form diopside with all the (Mg,Fe)O present, and titanite with all the TiO_2 present. Such a calculation indicates practically no other change in the composition than an increase in the percentage of lime from 1.30 to 2.97 per cent. The rock would contain 25.2 wt. per cent quartz, while the actual Becket gneiss has 27.7 wt. per cent.

The actual clinopyroxene gneiss in many cases differs from this imaginary rock in being poorer in quartz, and having soda in excess over potash or potash over soda. The aplitic gneiss around the skarn inclusions near Benson Pond is an example of a highly potassic type low in soda and silica, being composed practically of potash feldspar only. The analyzed rock from south Peru, on the other hand, is an extremely sodic variety, low in potash and silica. In both cases practically all the excess silica is gone, and the feldspars and the pyroxene only have been left.

Where a magnesic clinopyroxene occurs in an acid gneiss it proves that the assimilation of limestone had happened nearly in place without further development, while the occurrence of pyroxene high in the iron compound, as was found in some cases, indicates that some differentiation had taken place after assimilation. Both cases occur in the banded Becket gneiss (cf. p. 277).

The *skarn* exhibits a special case. It is supposed to be a pneumatolytic contact-product formed in limestone in such a way that adjacent magmas have brought in silica and metal compounds which have replaced the carbonate.

It is pretty clear, in the case of the clinopyroxene gneiss in question, that it has been formed in part by direct assimilation of limestone by the gneiss magma and in part by the assimilation of skarn previously formed by contact action.

The main indication of the banded structure of the gneiss seems to be that its intrusion and crystallization has happened

under the conditions of stress and movements. The effective stirring together of the earlier solid materials with the newly intruded mass doubtless was one of the chief reasons why assimilation of limestone on a rather large scale has occurred here.

Very obviously some amount of assimilation of older silicate rocks associated with the limestone has also taken place. Some evidences to this effect have been presented by Emerson.[1] In its actual characters, however, the banded gneiss is altogether an igneous rock and its band structure is not by any means a direct result of injection combined with some kind of ultrametamorphism. Its whole structure is markedly different from that of such injection gneisses and migmatites known to me from many other regions and, also, from the eastern boundary zone of the Becket gneiss west of Chester.

We may make some comparisons with similar phenomena in other regions. Such clinopyroxene gneisses, or clinopyroxene granites, occurring in connection with limestones and evidently formed by assimilation of limestones surely do occur in many tracts. That they are little noticed may in part be due to their inconspicuous aspect and often imperceptible difference in the hand specimen from ordinary granites and gneisses. On the other hand, it is quite certain that they are not by any means regular associates of granites intruding limestones. I shall name some examples from my own experience.

My work in the Orijärvi region in southwestern Finland proved the absence rather than the occurrence of such products of assimilation of limestone, although it is an area where gneissic granites are intrusive into limestone-bearing formations. Only in a few places was the boundary type of the gneiss granite against limestone found to be diopside-bearing,[2] and only where it intersected limestone as dikes. None of the granites designated as "microcline granite," which are distributed all through southern Finland and very often cut limestones or contain inclusions of them, was ever found to contain clinopyroxene as a rock mineral, excepting in pegmatite dikes (cf. below). Similar relations have also been

[1] *U.S. Geol. Surv., Bull. 597*, p. 154.

[2] P. Eskola, *Bull. Comm. géol. Finl.*, No. 40 (1914), p. 61.

found obtaining in the well-known limestone-bearing area of Parainen (Pargas).[1]

Another feature with which the non-occurrence of assimilation is evidently connected is that this granite which forms veined gneisses or migmatites with all kinds of siliceous rocks has never been intruded into limestones to form intimate mixtures. Therefore the writer made the following general statement:[2] "The resistance offered by limestones against granitization is very remarkable. Even in the midst of a migmatite area, where all siliceous rocks have been thoroughly mixed or assimilated with the granite magma, the limestones are generally quite free from granitic injections, and are intersected only by rectilinear dikes." More evidence of assimilation of limestone by granite magma was brought forth during an investigation of certain areas in Transbaikalia.[3]

The peninsula of Sviatoy Noss, on the east coast of Lake Baikal, is made up of crystalline schists, among which are numerous masses of limestones, and of huge batholiths and smaller bodies of granites intrusive into the schists. The granites, when meeting limestone either as dikes or as large masses, show no endomorphic change whatever at the contacts, while in certain intrusive masses there is a very remarkable change in the whole rock bodies, the rocks (called sviatonossite) being composed of alkali feldspars with aegirite-augite and andradite. The high percentage of lime present has clearly been derived from the limestone, but the process of assimilation has taken place in such a way that andradite-clinopyroxene skarn has first been formed from the limestone and the skarn has subsequently been absorbed. This is evident from the common occurrence of fragments of skarn in the rock showing every degree of assimilation. Finally, all the minerals have crystallized out from the magma and the rock is now an ordinary unaltered igneous rock.

[1] Laitakari, *op. cit.*

[2] *Op. cit.*, p. 36.

[3] P. Eskola, "On the Igneous Rocks of Sviatoy Noss in Transbaikalia," *Översikt av Finska Vet.-Soc. Förhandlingar*, Vol. LXII, A, No. 1 (1921).

On the island of Gurskö, on the west coast of Norway,[1] the writer studied a large mass of crystalline limestone surrounded by an intrusive gneiss. At the boundary of the limestone there occurs a zone in the gneiss consisting of a banded clinopyroxene-oligoclase rock. This rock undoubtedly has obtained some of its lime by assimilation of the limestone, and its characters are, in so far as regards the structure and probable mode of intrusion and consolidation during vehement movements, closely similar to those of the western Massachusetts rocks.

In all cases mentioned, acid magmas have been enriched in lime derived from limestones and have crystallized as such without any considerable change of composition through differentiation. We shall not discuss here at all those processes by which alkaline rocks are supposed to form from igneous magmas which have assimilated carbonates.[2]

Diopside pegmatites in limestone regions.—While rocks, in occurrence and origin similar to the diopside gneisses described, are uncommon, there are in most limestone areas cut by granites, very numerous dikes of pegmatite containing diopside, titanite, and other lime-bearing minerals. Such pegmatites occur so commonly in the western Massachusetts area[3] and elsewhere, that we do not need to give any further examples. The large quantity of titanite present in many of these dikes is remarkable.

The writer's field evidence from southern Finland goes to prove that the assimilation of lime has taken place within the pegmatite fissures themselves and not in the granitic parent magmas of the pegmatite. This is well illustrated by the frequently observed feature that a pegmatite, cutting through limestone and other rocks as well, has developed much diopside and titanite only while intersecting the limestone, but is an ordinary mica pegmatite outside of the limestone.[4]

[1] P. Eskola, "On the Eclogites of Norway," *Vid. selsk. Skri. Mat.-naturv. Kl. I*, No. 8 (1922), p. 24.

[2] As the writer has suggested, the Sviatoy Noss rocks show an incipient stage of development toward "alkalinity."

[3] B. K. Emerson, *U.S. Geol. Surv., Bull. 597*, p. 19.

[4] Cf. A. Laitakari, *op. cit.*, p. 7.

The pegmatites, like other igneous rocks, show a varying behavior toward the limestones: The writer has seen, in several limestone areas, swarms of pegmatite dikes some of which carry clinopyroxene and titanite whereas others do not and could find no differences to which this might be ascribed.

The common occurrence of phenomena of assimilation in pegmatites interests us because it proves decisively that this process does not require any high temperatures. The pegmatites crystallize out from residual solutions which still exist in liquid form after the main igneous bodies have become solid. The common occurrence of β-quartz as well as α-quartz proves that the temperature has frequently been below their transformation point at 575° during the crystallization of pegmatites.

Now, what has been the temperature of consolidation of the diopside-bearing varieties of the Becket gneiss? If we could estimate this, we would know that the assimilation took place at slightly higher temperatures than that of the beginning of crystallization. This must have happened between the three-phase points quartz-calcite-wollastonite and quartz-dolomite-diopside invariant under the existing pressure. The higher of these points apparently lies below the inversion-point α-quartz-tridymite, but at present we cannot state it more closely.

The other minerals of the gneiss indicate that the temperature had decreased very much before crystallization was complete. The rock contains epidote as individual large grains associated with albite, the epidote probably not being entirely of secondary origin. The potash feldspar does not contain any threads of albite (perthite), a fact that might indicate that the temperature was so low when the microcline crystallized that no considerable amount of albite could be taken into solid solution to separate later and form perthite. Only the lowest-temperature pegmatites contain such homogeneous potash feldspar.

Turning finally to the question why limestone is assimilated in some cases and in others not at all, it seems that this may be largely dependent upon mechanical conditions. Assimilation is promoted, if the intrusion is connected with folding and the intrusive magmas are agitated and mixed with the crushed materials from

the country-rock. This is in accordance with the experience that assimilation usually occurs where the intrusive rock shows banded structure and a high degree of protoclastic crushing and shearing, while it does not occur in masses which have been intruded and crystallized under quieter conditions and have come in contact with the country-rock along smooth surfaces only.

It does not seem, however, that the whole question can be covered by this explanation only. There are no doubt differences in the physicochemical conditions, in the concentration of volatile compounds, etc., which cause assimilation to occur in one case and not in another. Such relations may be understood better as soon as more experimental evidence has been gathered about the solubility of carbonates in magmas.

SUMMARY

Within the area of the igneous Becket granite gneiss in western Massachusetts there occur several tilted up layers of crystalline limestone, called Coles Brook limestone, older than the gneiss and metamorphosed by its contact influence. In the vicinity of the limestone the gneiss contains considerable quantities of lime-bearing silicates, especially of clinopyroxene (diopside-hedenbergite) and titanite, apparently the result of assimilation of limestone by the gneiss magma.

The gneiss is markedly banded, with alternating darker and lighter bands. It was found, by determining the refractive indices of the chief mafic minerals, biotite, clino-amphibole, and clino-pyroxene, that the amount of their magnesia compounds in proportion to their ferrous compounds increases with the total quantity of the mafic constituents. At the same time the amount of anorthite in the plagioclase increases. Thus the dark bands behave like the earliest separated rocks in a differentiation series. Some differentiation by crystallization really seems to have taken place after the assimilation. In certain places, however, and especially at the immediate contacts against the limestone, the actual composition of the gneiss appears to be a direct result of assimilation and no correspondence between Fe:Mg ratio and "basicity" exists.—The distribution of magnesia and ferrous oxide among the different

mafic minerals was found to show a certain regularity, the mica always being richest and the clinopyroxene lowest in the iron compound. The variation of the "Fe-quotient" is believed to offer an important characteristic of crystalline rocks, though at present little understood.

When silica-bearing limestones are subjected to metamorphism there occur reactions between the carbonates and silica, and silicates of lime and magnesia are formed. The temperature of reaction varies with pressure and is different for different minerals formed, as pointed out by V. M. Goldschmidt. The writer's earlier investigations have established that, among the common accessory silicates in limestones, wollastonite requires the highest temperatures to form, and diopside and tremolite, successively lower. At still lower temperatures silica, in the form of quartz, remains uncombined. Thus we may distinguish the following types of metamorphic limestone: wollastonite limestone, diopside limestone, tremolite limestone, and quartz limestone. These types may be used, under certain conditions, as a geologic thermometer, and it is hoped that the equilibrium curves of the different silicates with the carbonates may soon be determined experimentally.

The limestones of western Massachusetts were found to represent all the above-named types excepting the wollastonite limestone. Their mode of occurrence harmonizes with the writer's earlier experience, diopside limestone occurring at the immediate contacts of the gneiss and tremolite limestone and quartz limestone successively farther away.

A review of the writer's experience from limestone-bearing regions where intrusive granites occur seems to prove that such phenomena of assimilation of limestone as those observed in western Massachusetts are not at all of regular occurrence. Preferably they seem to occur in those regions where gneiss magmas have been intruded in connection with mountain folding, thus being dependent on the mechanical conditions in all probability. It appears, also, that assimilation does not require very high temperatures, being a very common phenomenon in granite pegmatite cutting limestones.

A CRITICISM OF THE "FAUNAL RELATIONSHIPS OF THE MEGANOS GROUP" BY BRUCE L. CLARK

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In a recent paper[1] published in the *Journal of Geology* Dr. Bruce L. Clark revises the Eocene scale of California by introducing a new division, the Meganos group, by cutting off the lower portion of the strata which had previously been referred to the lower Tejon. Clark's essential basis for division is stratigraphy first recognized in the area north of Mount Diablo, Contra Costa County. After his recognition of an unconformity in this area, subsequent faunal work led him to assert a marked faunal break as well although he recognized that the fauna obtained from these beds "appears to be more closely related to the Tejon than to the Martinez." In this paper Clark deals with the general correlation of the middle and upper Eocene Sections of the Pacific Coast and he tentatively correlates his Meganos group with the Wilcox of the Gulf Coast.

Owing to his absence from the United States, the writer is unable to discuss this paper in detail, but there are certain general conclusions of Dr. Clark's to which he wishes to record a firm dissent.

The evaluation of an unconformity is frequently a difficult matter and in many cases only a close study of the faunas from above and below the line of unconformity will enable the paleontologist to determine the relative value of the time break recorded in the rocks. Now the recognition of the existence of unconformities within the Tejon Group is not new, and largely upon this account the writer has consistently clung to the term *group* in describing the Tejon as a stratigraphic and faunal unit. In making a study of the Tejon Group, its probable future division

[1] Bruce L. Clark, "The Stratigraphic and Faunal Relationships of the Meganos Group, Middle Eocene of California," *Jour. Geol.*, Vol. XXIX (1921), pp. 125–65.

FIG. 1.—Outline map of California showing (1) Mount Diablo region; (2) region north of Coalinga; (3) south end of San Joaquin Valley; (4) Camulos quadrangle; (5) Table Mountain, in the vicinity of Oroville.

into formations was constantly kept in mind. In the special case in point the writer regards the unconformity north of Mount Diablo as being such a one as would separate the Tejon group into formations, while Dr. Clark would make two groups. Dr. Clark admits that this unconformity was not stratigraphically recognized in the fine Tejon-Eocene section only a few miles distant on the south side of Mount Diablo.

Detailed mapping has failed to show any marked difference in dip and strike between the Meganos and the Tejon in this southern area, such as occurs to the north of the mountain (Mount Diablo). At a few localities there is an apparent difference in dip between the beds of the two horizons; this, however, could not be verified with certainity, the division being recognized by a sharp change in lithology, and by faunal evidence [p. 141].

The footnote on this same page is likewise significant:

In the former paper ["Meganos Group, a Newly Recognized Division in the Eocene of California," *Bull. Geol. Soc. America*, Vol. XXXIX (1918), pp. 281–96] referred to above, the writer stated that in this section there is a marked difference in strike between the Meganos beds and those of the Tejon, and the difference was taken as one of the evidences of unconformity between the beds of these two horizons. Later work, however, has shown that this apparent difference in strike is, in part at least, the result of faulting. Also it was stated that to the east of this area the Meganos disappeared due to this unconformity. At that time the writer had not recognized that the so-called Tejon beds to the east, as described by Dickerson, were in part Meganos.

Concerning the presence of unconformities in other parts of California, Clark refers to his studies made in the vicinity of Coalinga and Simi Hills, Ventura County, as follows:

The results of this work show conclusively that beds of both Meganos and Tejon age are present in all of these areas, and that there is in each an unconformity separating the strata of those two series.[1] . . . . As seen between . . . . Domengine Creek and Cantua Creek (Coalinga Quadrangle), the upper beds of the Meganos consist of a white sandstone which was mapped by Anderson and Pack as a part of the Tejon. The contact between the Meganos and Tejon comes in between this sandstone and somewhat similar sandstones of the Tejon. It is, as a rule, marked by a conglomerate and is irregular at numerous localities. The sandstones below the contact, due to the unconformity, thicken and thin very noticeably along the strike. Also, at a number of localities the lower sandstones show a dip and strike appreciably different from those of the Tejon beds above. While these differences amount

[1] Evidently series is used loosely.

at the most to only a few degrees, it is sufficient to cause the lower sandstone layers to be cut off obliquely, and on the cliff sections they are seen to abut against the basal beds of the Tejon [pp. 143–45].

The writer cannot see how "the sandstones below the contact, *due to the unconformity* thicken and thin very noticeably along the strike" but rather thinks that the beds were deposited near shore and that the sandstone lenses into shale or the shale gradually grades into sandstone. If memory is correct, Anderson and Pack's mapping indicates that several comparatively thick members exhibit this same phenomenon on a great scale. Anderson and Pack, F. M. Anderson, Clarke Gester, and J. A. Taff had good opportunities to study this section and as far as I recall none of them recorded any notable dip differences. The writer did not do extended field work in this section, but from what was observed, he believes that careful search will bring to light several erosional unconformities in the region. That is, the Tejon group in this region was deposited under strictly littoral conditions, and from time to time comparatively slight emergences of the Eocene continental strand line are recorded by these erosional unconformities. Dr. Clark states that the lithology of the sandstones above and below this unconformity are essentially similar. This similarity is so close that a series of hand specimens from above would not be separable from a series from below if the two were mixed. Depositional conditions over the present sites of Simi Hills region and vicinity of Grapevine Canyon are characteristically littoral as indicated by both the fauna and the lithology.

The fauna of only fifteen species listed by Clark from San Emigdio Canyon on page 149 is entirely too meager upon which to base definite broad conclusions. Of these, eight are new species, one is only generically determined, two are doubtfully referred to described Eocene species. However, it is quite possible that the Turbinolia Zone of the Tejon Group (Meganos Group of Clark) may be present here.

Dr. Clark assigns the *Siphonalia sutterensis* Zone of Dickerson to his Meganos Group largely upon faunal grounds, since *Turritella merriami*, *Ancilla* (Oliverato) *californica,* and a few other forms are found at Oroville, Marysville Buttes, in the vicinity of Mount

Diablo, Camulos Quadrangle, and the Coalinga region. On pages 130 and 131 Clark states that

> After discussing the various Eocene sections, reasons will be given for correlating the beds referred to the Meganos group in these different areas in the Coast ranges with one another and with the marine Ione formation in the Sierra Nevada foothills, as mapped and described by Lindgren and Turner *not, however, including the type section of the Ione.*[1]

Why not discuss the type Ione? It is well described and at one locality has yielded a fair but determinable marine fauna containing Turritella *merriami* and other typical Tejon species. Also the strata of the type Ione clearly intergrade with the Tertiary Auriferous gravels of the Sierra Nevada foothills. Now the type Ione may be traced southward and connected with the Marine Eocene strata a half-mile south of Merced Falls where specimens of *Venericardia planicosta merriami* may be collected in abundance. Farther south, the stratigraphy of the Ione clearly demonstrates deposition by a sea transgressing from the west. North of the type section of the Ione, Lindgren and Turner have traced these beds through to Oroville. Dr. Clark in his historical review quotes from Dickerson's "Note on the Faunal Zones of the Tejon Group" as follows:

> A study of the relationship between zone 3, Mount Diablo region, and the Siphonalia sutterensis zone and their geographic position suggest that the uppermost strata of the Marysville Buttes and Oroville were deposited by a transgressing sea, and that only in favored places along the western borders of the Sierra have the latest Eocene sediments been preserved from erosion. Lava caps such as that of the older Basalt of South Table Mountain have preserved these youngest Tejon sediments which have heretofore been regarded as Ione.

This quotation creates the impression in the reader's mind that Dickerson's concept of the Tejon-Ione relations was purely theoretical, whereas such is not the case. The stratigraphy of the Ione at Bear Creek 20 miles south of Merced Falls, at Merced Falls, at Ione, at Oroville, all clearly indicate deposition by a transgressing sea in close proximity to an old Eocene shore. Into this Eocene sea the streams of the low mountainous Eocene upland poured their golden sands. The reader is referred to Dickerson's paper, "Stratigraphy and Fauna of the Tejon Eocene of California," for a full

[1] Dickerson's italics.

discussion of these essential matters. Clark has evidently missed the significance of this evidence as he states on page 162 of his paper that

> Dickerson attempted to establish the stratigraphic sequence of his upper faunal zone in relation to that of the typical Tejon indirectly, not having the two faunas in the same section. His idea that the Siphonalia sutterensis fauna is younger than that of the typical Tejon appears to have been founded principally upon what he considered evidence for different stages of evolution of certain pelcypods, such as *Venericardia planicosta merriami* Dickerson and *Cardium marysvillensis* Dickerson. He believed that the variety *merriami* was derived from the variety *hornii* Later stratigraphic work has shown that these species occur in a sequence the reverse of that which Dickerson originally supposed, the *Venericardia planicosta merriami* coming in beds older than those containing the variety *hornii*. The same is true of the other species, which were derived from typical Tejon species.

It is true, however, that the problem of Ione-Tejon relations was attacked with faunal weapons as well. Clark states that "Later stratigraphic work has shown that these species occur in a sequence the reverse of that which Dickerson originally supposed. . . . ." In the historical review on page 129, Dr. Clark reviews a short paper, by Arnold and Hannibal, and includes the following quotation from it:

> The writers have shown that in Oregon and Washington the Eocene may be divided into three faunal divisions, the Chehalis, Olequa, and Arago or Ione formations. The Chehalis formation is characterized especially by *Venericardia hornii* Gabb, Meretrix *californica*, *Pecten* (*Chlamys*) *landesi* or *Venericardia hornii* Gabb and a tropical flora, and the Arago or Ione formation by *Turritella merriami* Dickerson, a form of *V. hornii* with obsolete ribs (var. *aragonia* A. and H.), and a tropical flora.
>
> The Arago or Ione beds represent a horizon younger than any Tejon recognized in the Tejon or Puget Basin. The Arago or Ione beds occurring as they do in basins distinct from those in which the Tejon series is developed, and being formed at a different period, must be treated as a distinct division of the Eocene.

[1] Arnold and Hannibal use formation as an equivalent for faunal zone or horizon and loosely use *formation*, *group*, *series*. The form referred to as *V. hornii* var. *aragonia* A. and H. was not described by them but was collected at the type locality of *V. planicosta merriami*, on Little River, Roseburg Quadrangle, Oregon. Arnold and Hannibal classed these beds as Arago (or Ione).

In connection with this statement Clark refers to Weaver's stratigraphic studies wherein Weaver shows that the Olequa and Chehalis of Arnold and Hannibal were reversed. Weaver's careful work cleared up this succession but apparently does not invalidate Arnold and Hannibal's assignment of the Arago as the uppermost formation of the Eocene. Arnold and Hannibal regard the type locality of *Venericardia planicosta merriami*, on Little River, Roseburg Quadrangle, Oregon, as being in the uppermost portion of the Eocene, their Arago formation, and in this general conclusion the writer is in agreement. The evidence yielded by evolutionary forms of *Venericardia planicosta* have not been sufficiently studied by Dr. Clark. The first of these forms is *V. planicosta venturaense* Waring and was described from the Martinez (Lower Eocene) of the Simi Hills, Ventura County, California. Waring's type was considerably eroded but a mature specimen collected from near the type locality by the writer shows strong V-shaped ribs marked by very prominent nodes. Now these characters are conspicuous only in the youthful stages of *V. planicosta hornii* Gabb, the nodose character disappearing rapidly as the specimen matures. In very youthful specimens of *V. planicosta merriami* the same characters appear but these forms upon reaching maturity are marked by nearly complete obsolescence of ribs as well.

Clark, in the writer's opinion, overemphasizes the presence of new species in the Eocene and permits this to color his views. It is the writer's experience that in California, where unusually good preservation is found, many new species will be discovered. We must not lose sight of the fact that the pelecypod and gastropod fauna of the Tejon group is probably not much more than half-described. And on this account we must not create new horizons, based largely on such evidence. Again, let us not forget that the Tejon group is largely composed of inshore or strictly littoral sediments, and that the lignite seams occurring commonly throughout California, Oregon, and Washington, generally indicate deposition in lakes or lagoons bordering the Eocene shore. Thus during the deposition of the upper Tejon north of Mount Diablo three different carbonaceous beds were laid down, and there is evidence to show that the sea was at least temporarily withdrawn while these lignitic

strata were being formed. In other words, minor unconformities are here present. Sixty miles east of Mount Diablo there is a ten-foot seam of coal at Ione in the type section. Now if Clark is right in correlating the Ione with his Meganos group, then the Meganos group is again broken by an unconformity, since several hundred feet of Eocene sediments underlie the Ione coal seam which rests unconformably upon them.

Along the foothills of the Sierra Nevada in the undisturbed, nearly horizontal Eocene beds many interesting data are yet to be secured, as here the old Eocene shore is traceable and the streams of the old Eocene peneplain are still preserved beneath thick lava for the inspection of some untiring geologist interested in reconstructing the past of this wonderful land.

THE AGE OF THE DOMES AND ANTICLINES IN THE LOST SOLDIER–FERRIS DISTRICT, WYOMING[1]

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INTRODUCTION

The relative age of the major and minor folding in Wyoming is a somewhat mooted question among geologists, especially among those who are interested in the problems of oil and gas accumulation. In a recent paper Ball[2] reached the conclusion that nearly all the minor folds of Wyoming were formed during the period of formation of the major uplifts. That exceptions to this general rule may exist is frankly admitted by Ball, and he cites the Simpsons Ridge fold as the one example with which he is familiar of an uplift in which the minor folding is clearly younger than most of the major folding. Although agreeing in general with Ball's conclusion, the writer believes that exceptions to the rule are more numerous than Ball suggests. He believes further that a most noteworthy exception to the rule is to be found in the folds of the Lost Soldier–Ferris oil and gas district of south-central Wyoming, the age relations of which are here discussed.

GEOGRAPHIC AND GEOLOGIC RELATIONS

The Rawlins uplift, in south-central Wyoming, is about fifty miles in length and twenty miles in width and trends in a northerly direction (see map). It is not large enough to be classed among

[1] Published with the permission of the Director of the United States Geological Survey. The information presented in this paper was obtained in the summer of 1920, during an examination made to obtain data for classifying the public land in the oil and gas fields of the Lost Soldier–Ferris district. The results of this examination are being prepared for publication by the United States Geological Survey.

[2] Max W. Ball, "The Relative Ages of Major and Minor Folding and Oil Accumulation in Wyoming," *Amer. Assoc. Petroleum Geologists, Bull. 5* (1921), No. 1, pp. 49–63.

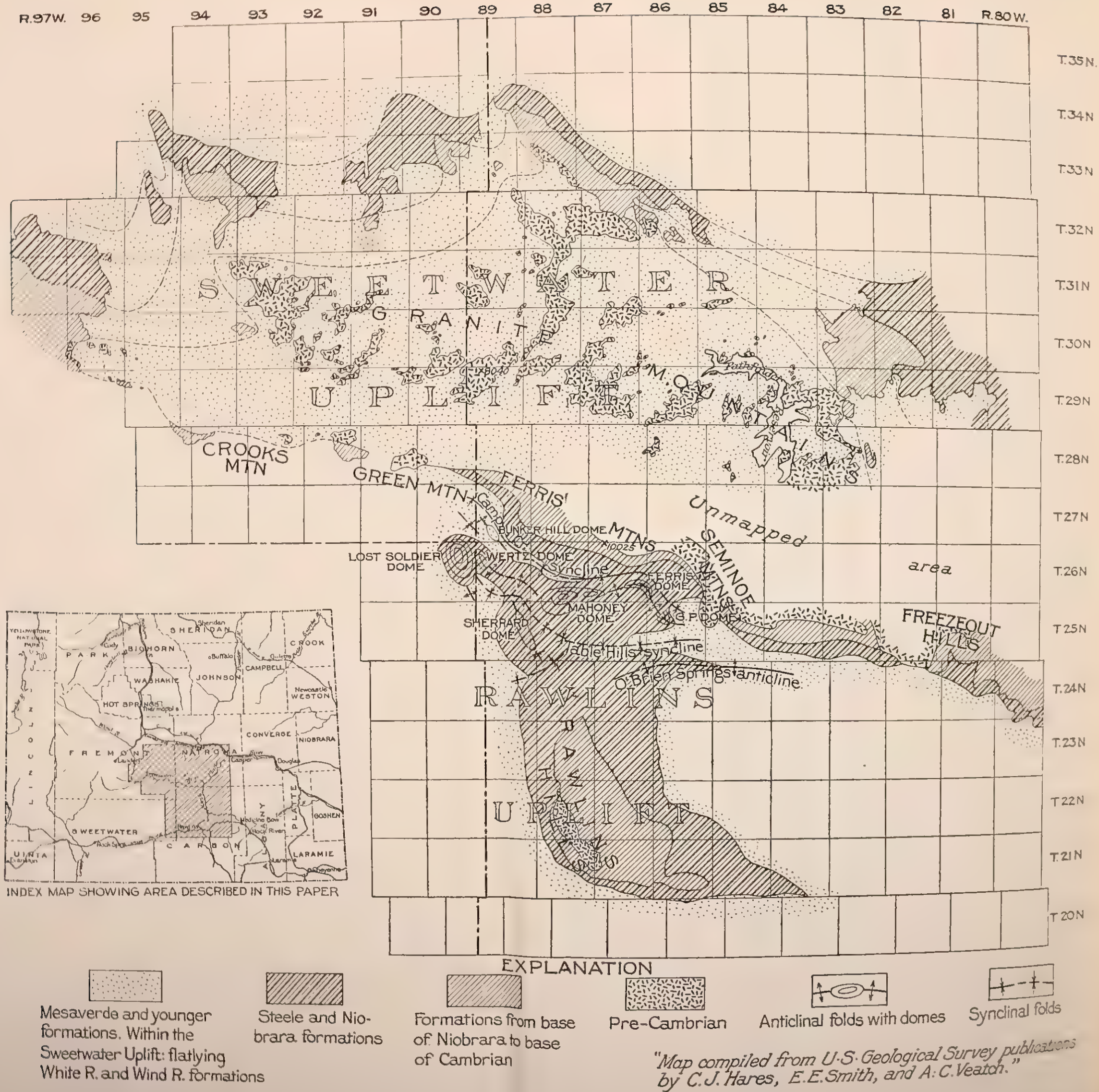
the major uplifts in Wyoming on account of its size, but the fact that its central axis is elevated so high that the pre-Cambrian rocks are now exposed at the surface is sufficient, as pointed out by Ball,[1] to justify ranking it as a major uplift. Its alignment makes it a part of that series of Rocky Mountain flexures characterized by northerly lines of folding and faulting. It is to be noted especially that the Rawlins uplift is one of a group that forms the northernmost member of this northerly series, beyond which the Rocky Mountain folds abruptly change in direction to a transverse series with east-west trend, of which the Sweetwater uplift, described below, is one.

From the general horizontal position of the Wasatch beds on the west flank of the Rawlins uplift, it seems certain that the development of this uplift was complete, or practically complete, by the beginning of Wasatch time.

The central pre-Cambrian granite core of the Rawlins uplift is faulted along its west side, and toward the north this fault zone turns northeastward and crosses the axis of the fold. The portion of the uplift north of this fault is on the down-dropped side, and this lower-lying north end of the uplift is occupied by the oil and gas fields of the Lost Soldier–Ferris district. The oil and gas accumulations of this district are controlled by minor folds, and it is these minor folds that constitute the subject of this paper.

North of the Rawlins uplift is the Sweetwater uplift, a major fold about one hundred miles long and forty miles wide that trends nearly due east. The Granite Mountains, which occupy the central part of this uplift, represent the higher peaks of the much dissected pre-Cambrian crystalline rock core, whose valleys and lower-lying parts are now filled and covered by nearly horizontal Tertiary sediments. These sediments form a nearly flat plain, above which the Granite Mountains rise like islands in a sea. On the south margin of the Sweetwater uplift, immediately adjacent to the Lost Soldier–Ferris district, are the Ferris and Seminoe mountains. The north side of the Ferris Mountains consists of pre-Cambrian crystalline rocks, adjacent to which, in a sharply upturned attitude, lie the Paleozoic and Mesozoic sediments that

[1] Max W. Ball, *op. cit.*, p. 51.



GEOLOGIC MAP OF THE RAWLINGS AND SWEETWATER UPLIFTS, WYOMING

form the south side of the mountains. In some places high on the flanks of the mountains the sedimentary beds are vertical or even slightly overturned.

To the southeast of the Ferris Mountains this sharp folding is replaced by faulting with thrust from the north, so that the crystalline rocks of the Seminoe Mountains now lie against the Cretaceous rocks of the Lost Soldier–Ferris district. The fault plane along which this overthrusting took place probably was almost vertical, and the horizontal displacement therefore slight, but even so the adjacent sedimentary beds of the Lost Soldier–Ferris district are somewhat overturned. It seems very probable that this overthrusting continues eastward as far as the Freezeout Hills. Westward from the Ferris Mountains the folding changes into faulting, but in this direction the amount of overthrusting is not so great as to the southeast.

The Sweetwater uplift, like the Rawlins uplift, is considered to have been developed mainly in pre-Wasatch time, but it differs from the Rawlins uplift in that the main deformation was followed by later movements of considerable magnitude. The importance and relations of these later movements are discussed below.

AGE OF THE FOLDS

The points to be brought out are two: (1) The folds of the Lost Soldier–Ferris district were not produced by the same forces that formed the Rawlins uplift, on which they were superimposed, but were produced by the forces that formed the Ferris and Seminoe mountains, to the north and northeast. (2) The Ferris and Seminoe mountains are considerably younger than the Sweetwater uplift, on whose south margin they rise, and probably represent a relatively late readjustment along this margin. If these points are established it follows that the folds of the Lost Soldier–Ferris district are younger than the Rawlins uplift and also younger than the main development of the Sweetwater uplift.

1. With the geographic setting of the Rawlins and Sweetwater uplifts in mind (Pl. III), attention should be directed to the alignment of the minor folds in the Lost Soldier–Ferris district. The downfold that structurally separates the Rawlins and Sweetwater

uplifts is the sharply flexed Camp Creek syncline, which lies only a few miles south of the Ferris and Seminoe mountains. It parallels the direction of the fault line along the southwest side of the Seminoe Mountains. North of this syncline there are no minor folds on the south slope of the Sweetwater uplift, but instead the abrupt upfold and thrust of the uplift itself, which is represented topographically by the Ferris and Seminoe mountains. South of the Camp Creek sycline the Rawlins uplift is represented by a long, comparatively gentle slope up to the granite axis of the upfold in the Rawlins Hills. This gentle north and northeast slope is interrupted by minor folds, including a long upfold that extends from the Wertz dome at the west and is accentuated in its eastward course by the Mahoney, Ferris, and G.P. domes. As the surface rocks are concealed by dune sand and alluvial wash the exact course of this upfold is not well known except at the high points mentioned. The axis of this upfold is parallel not to that of the Rawlins uplift but to that of the Camp Creek syncline, which in turn lies parallel to the Ferris-Seminoe line of deformation. From this close parallelism of structure it would appear that this minor upfold is the result either of the same forces that produced the Ferris and Seminoe mountains or of similarly directed forces. Certainly it could not have been the result of the forces that formed the Rawlins uplift. The north flanks of the Wertz and Mahoney domes and the northeast flanks of the Ferris and G.P. domes are steeper than the opposite flanks, a relation which also helps to indicate that the forces which formed them probably came from the north and northeast. To the north of the Wertz dome is the small Bunker Hill dome, which lies parallel to both the Wertz dome and the Camp Creek syncline. The course of the synclinal fold lying immediately south of the Wertz–Mahoney–Ferris–G.P. upfold is not clearly defined, although the syncline that separates the Mahoney dome from the Sherrard dome, and the Wertz dome from the Lost Soldier dome, is probably the westward extension of the Table Hills syncline. It was this downfold which divided the north end of the Rawlins uplift and formed the Lost Soldier dome as a distinct feature from the Wertz–Mahoney–Ferris–G.P. upfold, to the east. By considering the Table Hills syncline to have a westward extension, as above mentioned, its course also shows a

transverse direction to that of the Rawlins uplift and a parallelism to the Ferris-Seminoe line of deformation. The O'Brien Springs anticline, still farther south, shows a similar trend.

From the considerations above set forth it seems reasonable to suppose that the minor transverse folding in the Lost Soldier–Ferris district on the Rawlins uplift was produced by compressive forces that came from the direction of the Sweetwater uplift, to the north; and from the parallelism between these folds and the Ferris-Seminoe line of deformation, it seems reasonable to suppose further that these minor folds represent the more distant effects of the same forces that formed the Ferris and Seminoe mountains.

2. If the truth of the preceding arguments is conceded, there remains, to complete the purpose of this paper, proof that the minor folds of the Lost Soldier–Ferris district are decidedly younger than the major Rawlins uplift and the main development of the Sweetwater uplift. It has been shown that the axes of the minor folds are transverse to those of the Rawlins uplift, a relation which in itself implies, although it does not necessarily prove, that the minor folds are more recent than the uplift itself. The best proof, however, is to be found in showing that the Ferris and Seminoe mountains, which are of the same age as the minor folds of the Lost Soldier–Ferris district, are considerably younger than the main development of the Rawlins and Sweetwater uplifts.

The Ferris and Seminoe mountains may be spoken of as a marginal rim to the Sweetwater uplift. The central core of this uplift, now represented by deeply eroded granite, is a structurally much more highly elevated part of the uplift than the Ferris and Seminoe mountains at its margin. It is possible that at the time of the main deformation the central core of this major uplift was elevated to several times the height of the marginal rim; but the particular fact to be noted is that the Ferris and Seminoe mountains now attain a maximum altitude of 10,025 feet (as determined by triangulation and vertical angles), a considerably higher altitude than that of the peaks of the Granite Mountains, which now form the core of the uplift, and whose highest point, Hayden Peak, is reported by Hares[1] to have an altitude of only 8,040 feet. This

[1] C. J. Hares, "Anticlines in Central Wyoming," *U.S. Geol. Survey Bull. 641* (1916), p. 234.

difference of nearly 2,000 feet in altitude cannot be due to difference in erosion alone. Moreover, the Granite Mountains now show smooth surfaces, whereas the Ferris and Seminoe mountains are rough and rugged, a difference which indicates that the Ferris and Seminoe mountains are in a more youthful stage of erosion.

From these differences in altitude and in character of topography, therefore, it appears clear that the present Ferris and Seminoe mountains are younger than the Granite Mountains. This conclusion further indicates that the Ferris and Seminoe mountains are probably the result of a relatively late readjustment along the south margin of the Sweetwater uplift, and, from the nature of the structural features in this region, that this later deformation was a slight overthrust in which the Sweetwater area moved southward toward the Rawlins uplift.

How much later in geologic time than the main development of the Sweetwater and Rawlins uplifts this readjustment took place is not readily ascertainable. From unpublished field information pertaining to T. 28 N., Rs. 90 to 95 W., along the south edge of the Sweetwater uplift, gathered by Hares just beyond the south margin of the area covered in his report on "Anticlines in Central Wyoming,"[1] and by Smith along the north margin of the area covered in his report on "The Eastern Part of the Great Divide Coal Field, Wyoming,"[2] it is clear that there has been considerable readjustment in these townships since pre-Wasatch time, when the major upfolds were first developed. The significant evidence along this marginal zone is to be found in the nearly flat-lying Tertiary formations (Wasatch ?) in the Green and Crooks mountains, at altitudes of 1,000 feet or more above the nearly flat-lying Tertiary beds (Wind River and White River formations) of the basin that now marks the Sweetwater uplift. It is also an interesting fact that the White River (Oligocene) formation of the Sweetwater basin—the "sea" in which the Granite Mountains stand out as "islands"—seems to be limited on the south by the fault zone that marks the boundary between the pre-Cambrian rocks of the Sweetwater uplift and the Paleozoic and Mesozoic formations in

[1] C. J. Hares, *op. cit.*, pp. 233–79.

[2] E. E. Smith, *U.S. Geol. Survey Bull. 341*, pp. 220–42.

T. 28 N., Rs. 89 to 95 W.[1] This greater altitude of the nearly flat-lying Tertiary beds south of the Sweetwater uplift and the possibility that the White River and Wind River formations lie only on the uplift itself are indicative of a readjustment movement here in post-Wasatch time and possibly as late as White River time. Ball[2] mentions the fact that the Hanna formation (Wasatch ?) is vertical and overturned in the Freezeout Hills.

There has even been some post-Pleistocene movement in the region, for gravel-covered terraces in some places are reported to have slopes opposite to those of the present drainage.[3] These comparatively recent movements were probably of small magnitude and are cited principally to indicate that deformation did not necessarily cease here in the Tertiary period, but that warping has occurred in the Quaternary. It is possible that deformation has taken place even within recent times.

Inasmuch, therefore, as mountain-forming deformation has occurred here in post-Wasatch time and possibly as late as White River (Oligocene) time, or even later, it would seem that the Ferris and Seminoe mountains should be regarded as the local results of this late movement of readjustment along the south margin of the Sweetwater uplift. Although the exact time when these mountains were formed has not been ascertained, it seems nevertheless that they must be considerably younger than the main deformative movements which produced the Sweetwater and Rawlins uplifts. If it is regarded as established that the Ferris and Seminoe mountains are due to a late and possibly final spasm of mountain-forming movements in this general region, it should probably be conceded that the minor domes and anticlines of the Lost Soldier–Ferris district are also due to the same movements. Credit must be given to Ball[4] for his recognition of a marked difference between the deformation features of the Ferris and Seminoe mountains and those of the Wyoming mountains of the

[1] No positive statement to this effect can be made, for the relation was noted over only a small area by the writer, and the evidence gleaned from the unpublished work of Hares and Smith above cited, though apparently supporting the inference, does not fully confirm it.

[2] *Op. cit.*, p. 55.

[3] K. C. Heald, personal communication.

[4] *Op. cit.*, p. 59.

usual type, but although he realized that this difference existed, he did not consider its significance in relation to the age of minor folds of the Lost Soldier–Ferris district.

ECONOMIC CONSIDERATION

The minor folds of the Lost Soldier–Ferris district are shown above to be distinctly younger than the Rawlins uplift, on which they are superimposed, and the question arises as to the relation of this difference in age to the accumulation of the oil and gas in the Lost Soldier, Wertz, Mahoney, Ferris, and G.P. fields. As the Rawlins uplift was in existence in pre-Wasatch time, it is obvious that any oil and gas that prior to the minor folding of the Lost Soldier–Ferris district had been formed or had migrated a short distance above the margin of the uplift, where the catchment areas of the present fields are situated, must surely have been lost through the eroded edges of the formations on the top of this major uplift. The oil and gas of the present fields and of possible unproved pools in this region must have been formed largely by the dynamo-chemical action of the later deformational forces that caused the minor flexing. Some oil and gas of earlier distillation may have been already present within the catchment areas of the existing fields, but this oil and gas must have been only a fraction of that which was formed within the area embraced by the Rawlins uplift. The oil and gas now available in this district for the use of man must represent, therefore, merely a remnant of the total quantity derived from the mother-material which the rocks of this region originally contained.

ON THE OCCURRENCE OF AN APUS IN THE PERMIAN OF OKLAHOMA

RUDOLF RUEDEMANN
New York State Museum, Albany, N.Y.

Professor J. W. Beede last year sent two specimens of a crustacean from the Permian of Oklahoma to the New York State Museum for investigation. They were from a suite collected by Dr. Thomas T. Jackson in a thin sandstone bed of the Enid formation, exposed "on the top of a hill four or five miles north of Elkeno, Oklahoma."

The specimens[1] proved, on inspection, of exceptional interest for the reason that they not only exhibit an outline of the carapace as seen in Apus but even the impressions of the "shell-glands" or excretory organs in a form as it is today known in Apus, and its close relative Lepidurus. We have, therefore, no hesitation in considering this Permian form a true Apus, and propose for it the name *Apus beedei* sp. nov.

Apus beedei sp. nov.

Description.—Carapace small (the larger specimen 15 mm. × 14 mm.); broadly elliptic, nearly circular in outline, with a small posterior emargination; shieldlike and sloping from the subcentral apex abruptly forward, more gently backward, and probably originally fairly steeply toward the lateral margins. A transverse cervical fold is situated about one-fifth of the length of the carapace posterior to the anterior border. Immediately posterior to this are the large but slightly curved "shell-glands" or excretory organs; beginning at either side of the median line they extend obliquely backward about midway of the lateral faces of the

[1] Professor Beede had stated in his letter that he had more specimens than the two sent but none showing features not seen in the ones inclosed. On inquiry, we learn that this further material is not available at present, but in view of Professor Beede's statement and the great interest of the material, we venture to publish this notice without having had access to the less favorably preserved specimens.

carapace to about one-fifth of the length of the carapace from the posterior border. The median line is marked behind the cervical fold by a distinct depression extending about one-third of the distance toward the posterior border.

Horizon and locality.—Permian (Enid formation), near Elkeno, Okla.

Note on identification with Apus.—The writer is well aware that considering the enormous stretch of time from the Permian to the present time, and further the fact that only the carapace of the

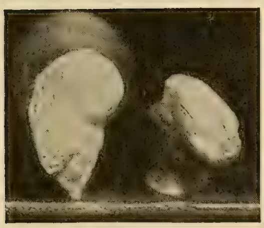


FIG. 1

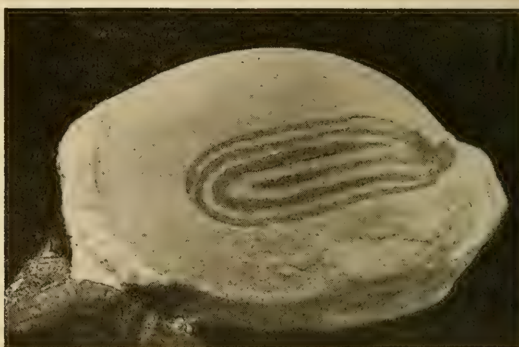


FIG. 2

FIG. 1.—*Apus beedei* sp. nov. The two specimens seen obliquely from above and the front. Natural size. The type-specimen is on the right. It shows the transversal wrinkle in the place of the cervical fold, portions of the frontal part of the carapace and the median depression.

FIG. 2.—*Apus beedei* sp. nov. Lateral view of the type-specimen. ×3. Shows the shell-gland and posterior emargination.

Permian form is now at hand, there is a great possibility that if the body of the animal were preserved, differences of generic importance might be quite apparent, e.g., such as now separate Lepidurus from Apus and which consist in the different development of the post-anal plate. It could, therefore, be urged that this Permian form should be made a séparate genus on theoretic grounds. In such an attempt it would, however, be found that the carapace of the older form is not distinguishable from that of the recent type and the new genus would have no diagnosis, but only its great age to stand on. It is, however, to be understood

that the term Apus expresses here the hard parts only and the entire group (Apus and Lepidurus) and that it is merely intended to point out the persistence of the Apus-type of carapace. The persistence of the exact form of the carapace in the group indicates that no evolutionary development profound enough to affect the carapace took place in all this time.

Note on preservation of material.—The specimens are casts of the interior surface of the carapace. It is for this reason that the impressions of the shell-glands are so well preserved in some of the fossils, for it must be remembered that these organs are situated between the two layers that form the posterior portion of the

FIG. 3

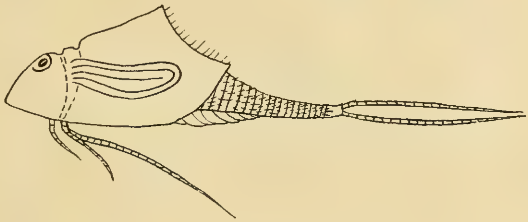


FIG. 4

FIG. 3.—*Apus beedei.* Flat projection of outline of carapace.

FIG. 4.—Lateral view of *Apus aequalis* Packard, ×2; from Colorado and in N.Y. State Museum.

carapace, and that these glands open where the inner layer terminates at the cervical fold. The frontal portion of the carapace is poorly preserved, partly no doubt on account of the greater thinness of the carapace there, which consists of but one layer, and partly owing to the lateral compression of the tests during entombment. There is, however, enough left of the frontal outline (especially in the smaller specimen) to leave no doubt that it was rounded and unbroken originally. It would seem that the shield was sufficiently sloping toward the lateral margins to come frequently to rest on the side and then suffer lateral compression. The amount of lateral slope is greater also in the recent Apus than the usual dorsal views of the creatures would suggest, as shown in the lateral view drawn from nature by the writer and reproduced in Figure 4. A restoration of the dorsal view of the carapace of *Apus beedei* is given in Figure 3. It is obtained by plotting the

larger specimen, in natural size, on the horizontal plane. An oblique view from above of the same specimen is given in Figure 1 and a lateral view in Figure 2. The former presence of a cervical fold in the Permian form, corresponding to that in recent species of Apus (Fig. 4, where it is shown in the profile behind the eye), is indicated by a transverse wrinkle, especially distinct in the larger specimen, but also seen in the smaller one. This wrinkle has resulted from the yielding of this transverse fold during lateral compression. It has thereby become pressed downward and changed into a deep transverse wrinkle, in front of which the carapace has split and been drawn inward. The smaller specimen retains the frontal portion in more perfect form, though also much compressed. Owing to this folding-in of the frontal part, the perforations of the carapace for the eyes are not observable.

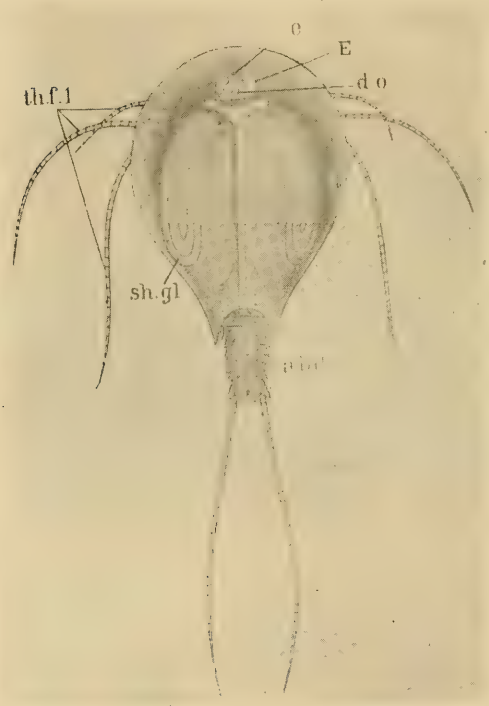


FIG. 5.—*Apus cancriformis* Schäffer. Dorsal aspect. From Parker and Haswell (after Bronn's Thierreich). *d.o.*, dorsal organ; *E*, paired eye; *e*, median eye; *sh. gl.*, shell-gland.

The shell-gland appears as an elongate elliptic body consisting of two concentric furrows and one median and another outer longitudinal one. There are thus altogether six urinary tubes counted on the transverse line, just as in the recent Apus (Fig. 5). All these are very distinct on both sides of the larger specimen and also well recognizable on the smaller one. They bend inward and

downward at the cervical fold, where as in the recent form they open (at the underside of the body).

The median line of the carapace is marked in its anterior third behind the cervical fold by a deep depression, fading out backward, which corresponds to the carina seen in *Apus cancriformis* and some of its congeners.

The posterior emargination is distinct in both specimens though not appearing in the photographs. The original of Figure 2 is just sufficiently compressed obliquely to have the emargination transferred to the other side.

General bearing of discovery.—Apus has long been famous in paleontologic literature as a primitive phyllopod that on account of its great number of simple appendages and other primitive features has served well as a model for comparison with extinct crustaceans, especially with the trilobites; and again in the case of the wonderful middle Cambrian branchiopods discovered by Walcott in British Columbia. It is equally famous among zoölogists for its strange life-cycle as well as its archaic characters. Notwithstanding its frequent citation in paleontologic literature, a true Apus has only once been found in fossil state. This is the *Apus antiquus* Schimper from the Buntsandstein of the Vogesian mountains. This find carried the range of Apus back to the Triassic, and the occurrence in Oklahoma extends it now to the Permian.

Apus is thereby made one of the few persistent types that have existed from Paleozoic to recent time. Like Limulus it is a "living fossil." Connected with this amazing persistence is undoubtedly the strange life-cycle of this creature, as the writer will elaborate more fully in another paper. Apus, as typically represented by *Apus cancriformis*, appears only at long intervals, usually only after decades of years, during which the eggs were buried in the dry mud of roads, ditches, and desiccated pools and exposed to heat and cold. It is therefore an extremely rare animal and the writer still remembers with thrill, how when still a schoolboy he one day espied a large specimen crawling on the muddy bottom in the water of a swamp along which he was botanizing,

rushed in, grabbed the strange creature, and ran back at top speed to the high-school professor of biology who promptly took it away declaring it to be the first he had ever seen alive! It is told of Goethe that he had one brought to him while walking once near Jena and that he became so excited over the weird animal that he offered a thaler for the second, a guilder for the third specimen, and so forth, but no other was found. *Apus cancriformis* grows within two weeks to full size which sometimes is nearly five inches, lays an enormous number of eggs and dies.[1] Another strange fact connected with this animal is that it produces the eggs parthenogenetically. It was fully a hundred years after the description of the species that any males were found. The seventy pairs of appendages (among them fifty-two pairs of abdominal feet with their gill-appendages) which give it its archaic appearance are also connected with its life in very temporary pools that lack the vegetation which oxygenates the water.

All these facts show that the animal is adapted to most peculiar, and it would seem also most precarious, conditions. It has been therefore thought by some, as Salter and Packard,[2] to be, together with the rest of the Branchiopoda, highly specialized and comparatively modern. Its fossil record, however, contradicts this conclusion, and from evidence, which the writer[3] in a former paper on arrested evolution has brought forward in regard to the factors of persistence in animals, it follows that Apus belongs to that class of persistent forms, that, at the height of their once vigorous development, were able to penetrate into fields where weaker forms could not follow them and it is precisely in these outskirts of the arena of organic struggle that these types, after they were overtaken by more rapidly developing forms, have managed to persist. This would suggest that Apus had followed its present mode of life through many periods, and the fossil evidence does not contradict this suggestion; for the single Apus found in the Buntsandstein may well have drifted in, together with the numerous remains of landplants (Voltzia, etc.) found in that Triassic terrane. Regarding the character of the Oklahoma deposit, from which our speci-

[1] Weigand, 1913.

[2] See Schuchert, 1897, p. 675.

[3] Ruedemann, 1918.

mens came, Professor Beede writes me under date of December 14, 1921, that it might be brackish water or, possibly, even fresh.

Leaving out the *Apus dubius* Prestwich, described from the Coal Measures of England, which, according to Beecher,[1] "seems to be an abdominal segment or plate of some eurypterid," there is evidence of a still older form, at least closely related to Apus, even in the Lower Cambrian. This is the well-known *Protocaris marshi* Walcott from the Waucoban (Georgian) of Georgia, Vermont. Its similarity to Apus was recognized by Walcott[2] and has since been commented upon by Clarke[3] and Bernard,[4] the latter author even proposing to call the form *Apus marshii.*[5] This Cambrian relative has also been found in but a single example and therefore was hardly a common marine form, as the tribolites collected in the same beds. Therefore, even this might have drifted in from the fresh water.

As to the remaining fossils that by some have been compared with Apodidae, we refer to Pompeckj's excellent summary in the chapter "Crustacea" in the *Handwörterbuch der Naturwissenschaften.*[6] The remarkable crustacean-fauna discovered by Walcott in Burgess-Pass contains both Notostraca (Burgessia and Naraoia) and Anostraca (as Opabinia, Leancholia, Yohoia), but not any forms that are directly referable to Apus, though some may, according to Pompeckj, be ancestral to later apodids, as Naraoia to the later Carboniferous Dipeltis, which behind the parabolic carapace possesses two large thoracic segments or rather shields.[7] The position of certain finds is considered doubtful, as that of a carapace, similar to Apus, described as *Lynceites ornatus* Goldberg from the Carboniferous of Saarbrücken and now currently referred to the Cladocera. There are further to be mentioned the problematic, laterally compressed carapaces of Ribeiria Sharpe and Ribeirella Schubert and Waagen, which occur in the Ordovician and Silurian of Bohemia, Portugal, England, and North America, and which were placed by Schubert and Waagen with the Apodidae

[1] See Schuchert, 1897, p. 675.

[2] 1884, p. 50

[3] 1893, p. 799.

[4] 1894, p. 413.

[5] Schuchert (1897, p. 674), however, points to the subquadrangular shield and frontal emargination as distinguishing characters.

[6] Pompeckj, 1912, p. 789.

[7] Schuchert, *op. cit.*

and considered as possible ancestors of Apus. Pompeckj holds that neither this nor the leptostracan nature of these fossils can be proved. We believe that the two muscle-impressions which Ribeiria shows on the dorsal median-line[1] indicate that in this form the carapace was attached to the body in nearly its entire length along the dorsal line while in Apus it is free from the cervical fold backward, i.e., in its greater portion. This would already indicate a very different organism, even if the deep transversal sulcus in front of the apex of the casts of Ribeiria could in some way be compared with the cervical fold in the carapace of Apus.

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1918. RUEDEMANN, R. "The Paleontology of Arrested Evolution," *New York State Mus. Bull. 196*, p. 107.

[1] *Ribeiria compressa* Whitfield, *Bull. Amer. Mus. Nat. Hist. N.Y.*, Vol. I, No. 8 (1886), Pl. 33, Fig. 3.

Petrological Abstracts and Reviews

Campbell, Robert. "Rocks from Gough Island, South Atlantic," *Trans. Roy. Soc. Edinburgh*, Vol. L (1914), Part II. Pl. 1.

Describes various igneous rocks collected by the Scottish National Antarctic Expedition, 1902–4.

Clapp, Charles H. "Geology of the Igneous Rocks of Essex County, Massachusetts," *U.S. Geol. Surv., Bull. 704* (Washington, 1921). Pp. 132, pls. 18, maps 2.

In this report is given a summary of previous work done in this interesting region of alkalic rocks, and considerable new or unpublished data are added. Two groups of rocks are recognized, an older subalkaline group consisting of granites, granodiorites, quartz-diorites, gabbro-diorites, and gabbros, and a younger alkaline group consisting of alkali-granites, alkali-syenites, and nephelite-syenites, with some diorite, diabase, and gabbro. There are many varieties of dike rocks, quartz-porphyries, paisanites, sölvsbergites, tinguaites, diabases, camptonites, vogesites, kersantites, minettes, fourchites, quartz-keratophyres, etc. The petrographic descriptions are fairly complete, many analyses are given, some of the modes are determined, and the structural relations are described. Of the essexite of Salem Neck, the author says (pp. 124–25): "It is not a differentiate of the alkaline or nephelite syenite but is a contact-metamorphosed gabbro or gabbro-diorite of the Salem type or in some places a metamorphosed olivine-bearing diabase. The schistose varieties and the more siliceous varieties of essexite, such as those containing microperthite, considerable nephelite, and large fawn-colored augites, are true hybrid rocks."

Cockfield, W. E. "Sixtymile and Ladue Rivers Area, Yukon," *Canadian Geol. Surv.*, 1921. Pp. 60, pls. 6.

This report, largely stratigraphic and economic, contains general descriptions of various schists, amphibolites, granite-gneisses, pegmatites, andesites, diabases, rhyolites and granite-porphyries, and various ash beds and sediments.

COLLINS, W. H. "The Age of the Killarney Granite," *Canadian Geol. Surv., Museum Bull. 22* (1916). Pp. 12, pl. 1, map 1.

The Huronian formations along the coast of Lake Huron have been greatly folded and faulted, and intruded by granite batholiths. Both disturbance and granite invasion were completed long before Ordovician time.

COLONY, R. J. "Petrographic Study of Portland Cement," *School of Mines Quart.*, Vol. XXXVI (1914), pp. 1–21. Figs. 14, bibliog. 14 items.

Gives petrographic criteria by which the fitness of cement and concrete may be judged.

DALY, REGINALD A. "Petrography of the Pacific Islands," *Bull. Geol. Soc. Amer.*, Vol. XXVII (1916), pp. 325–44. Bibliog. 58 items.

Concludes that underneath the Pacific Ocean the only primary magma is basalte, that pyroxene andesite and picrite are direct differentiates from it, and that the alkaline rocks may possibly be due to the solution of small proportions of limestone. There is a nine-page alphabetic list of the various islands with the different rock types occurring on each, and a list giving the number of islands from which the various rocks have been reported.

DALY, REGINALD A. "The Geology of Pigeon Point, Minnesota," *Amer. Jour. Sci.*, Vol. XLIII (1917), pp. 423–48. Figs. 5.

Believes that the "red rock" originated through both assimilation and differentiation rather than through the differentiation of a wholly primary magma, but says a final decision concerning its origin must for the present be delayed.

DALY, REGINALD A. "Metamorphism and Its Phases," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 375–418.

Proposes to classify metamorphic processes as follows:

A. Regional metamorphism.
   1. Static metamorphism.
      a) Stato-hydral or hydrometamorphism (low temperature).
      b) Stato-thermal or load metamorphism (high temperature).

2. Dynamic metamorphism.
   a) Dynamo-hydral or slaty (?) metamorphism (low temperature).
   b) Dynamo-thermal or friction (?) metamorphism (high temperature)
3. Dynamo-static metamorphism.

B. Local metamorphism.
1. Contact metamorphism.
2. Load-contact metamorphism.

DRESSER, JOHN A. "Granitic Segregations in the Serpentine Series of Quebec," *Trans. Roy. Soc. Canada*, Vol. XIV (1921), pp. 7–13.

Granitic dikes are limited to the peridotite-serpentine area of this region, and are believed to be local fillings of contraction cracks in the cooling peridotite by part of the still liquid acidic magmatic residues. Larger irregular masses are believed to be residual segregations from the magma of the peridotite and to have been formed *in situ* by differentiation.

DU TOIT, ALEX. L. "The Karoo Dolerites of South Africa: a Study in Hypabyssal Injection," *Trans. Geol. Soc. South Africa*, Vol. XXIII (1920), pp. 1–42. Figs. 5.

The uneroded remnants of strata invaded by these South African "dolerites" (British usage) cover fully 220,000 square miles, and fully half as much more has been removed. The rocks are composed of labradorite and augite, with or without olivine, and are of ophitic texture. They are almost exclusively confined to beds of the Karoo system, and date from the Rhaetic or Lias, Middle Jurassic at latest. The intrusions form intersecting dikes and a series of sheets, one above the other. The latter are practically horizontal and vary in thickness from 100 to 3000 feet, although in some cases still thicker sheets are found. Thus the curved sheets of the Queenstown district attain a thickness of fully 1,500 feet and cover some 40 square miles, and the Ingeli mass is over 3,000 feet in thickness. Metamorphic action is practically confined to baking of the sandstones and shales into quartzite and hornstone. With the exception of a few isolated and small-scale cases, no signs of assimilation of the strata by the invading magma were found. The sheets, with the exception of decrease in size of grain at the margins, are generally uniform in texture. In a few localities, enstatite partially or

wholly replaces augite, and the rock has a gabbroidal texture; in others there are more acid phases, and the rock passes through quartz-dolerites and diorites to granophyres and granites. All such departures are thought to be due to post-injection into the cooling body, or pre-injection into the intercrustal reservoir. The intrusive sills belong to one period of injection, and all phases were completed within a relatively short time. Disbelieving that the intrusion could have taken place at one time, owing to the fact that the slabs of sediment maintained their orientation, Du Toit thinks that they were injected progressively from the summit downward to the base, a mode of injection which he describes as decensional *lit-par-lit* stoping.

EGGLESTON, J. W. "Eruptive Rocks at Cuttingsville, Vermont," *Amer. Jour. Sci.*, Vol. XLV (1918), pp. 377–410. Figs. 5.

The eruptive body at Cuttingsville, Vermont, is thought to be a composite stock, all of the rocks presumably coming from a single magma. Essexite was the earliest intrusion, and nordmarkite the last. Hornblende-biotite-syenite, pulaskite, foyaite, and sodalite-nephelite-syenite probably came between these two in about the order given. The order of intrusion of the dikes is likewise from basic to acid. Essexite-porphyries were earliest, some of them perhaps apophyses from the essexite body. Aplite came after nordmarkite, and between these there were syenite-porphyries and pulaskite-porphyries. There are also dikes of tinguaite and of camptonite. The descriptions are not always clear. Thus under essexite it is said that the plagioclase ranges from Ab_7An_3 to Ab_3An_7, but it is not stated whether this is zonal, whether two different plagioclases occur in the same section (!), or whether the plagioclase differs in different parts of the area. A system of classification unknown to the reviewer is used, for the statement is made that "the abundant plagioclase allies it [the so-called syenite] to monzonite, but the ratio of dark silicates to feldspar warrants the designation of the rock as a hornblende-biotite-syenite." When it is stated that the "pyroxene is next to the feldspars in abundance," one imagines that it must be present in approximately the same quantity, yet the amount of feldspar is given as 90 per cent, sodalite as 3 per cent, and nephelite 3 per cent, leaving 4 per cent to be divided among pyroxene, biotite, apatite, magnetite, titanite, and possibly pyrite. The norm shows 2.35 per cent of corundum, but no feldspathoid. With five good rock analyses and an analysis of the hornblende, more carefully modal percentages would have been very instructive.

Eitel, W. "Über das Vorkommen von Zinkblende im Basalt des Bühls bei Cassel," *Centralbl. f. Min.*, etc., 1920, pp. 273–85. Figs. 6.

Describes the occurrence of zinc blende in basalt. At an unknown depth, the erupting basalt broke through dikes of blende with a little pyrite and much quartz. Included fragments of the dike rock were assimilated and recrystallized.

Eitel, W. "Bemerkungen zu einer Untersuchung von Lewkonja über die von Hornstein im Basalt des Bühls bei Kassel gefundenen Eisenknollen," *Senckenbergiana*, Vol. II (1920), pp. 130–33. Figs. 2.

Native iron, from the basalt of the Bühl, near Cassel, is described.

Eitel, W. "Bemerkungen zu chemischen Untersuchungen des Herrn F. Flade über das Eisenvorkommen im Bühl bei Cassel," *Senckenbergiana*, Vol. II (1920), pp. 158–63.

Gives an early (1909?) chemical analysis of the Bühl native iron.

Eitel, W. "Studien über die Genesis der Einschlüsse des Bühlbasaltes," *Abhandl. d. Senckenbergischen Naturforsch. Gesellsch.*, Vol. XXXVII (1920), pp. 139–76. Figs. 29.

Among the separate studies in this paper are the following: On pseudomorphs of pyrrhotite after pyrite in the Bühl basalt; on the origin of the magnetite inclusions in the Bühl basalt; a comparative study of the native iron from Ovifak and Bühl; on the genetic relationship of the native iron to the inclusions of pyrrhotite and magnetite; the relationship between the strata penetrated by the Bühl basalt and the inclusions in the latter; experimental studies on the formation of pyrrhotite from pyrite at high temperatures; on the occurrence of a sillimanite-graphite rock with pseudomorphs of spinel, rutile, and enstatite after garnet as an inclusion in the Bühl basalt; and the gas reactions in the Bühl basalt and their rôle in the origin of the native iron.

Eskola, Pentti. "The Mineral Facies of Rocks," *Norsk, geol. tidskrift*, Vol. VI (1920), pp. 143–94.

Metamorphic rocks, by recrystallization, may arrive at a state of chemical equilibrium. The term "metamorphic facies" is here used to designate a group of rocks characterized by a definite set of minerals

which were at perfect equilibrium with each other under the conditions of their formation. Igneous rocks, likewise, may reach a state of equilibrium, and igneous and metamorphic facies may be spoken of together as mineral facies. Mineral facies, therefore, comprise all rocks which have originated under conditions of temperature and pressure so similar that from a definite chemical composition there results the same set of minerals, regardless whether formed by primary crystallization or by metamorphism.

Eskola, Pentti. "On the Igneous Rocks of Sviatoy Noss in Transbaikalia," *Överskit av Finska Vetensk.-Soc. Förhand.*, Vol. LXIII (1920–21), pp. 1–99. Figs. 9.

This is an abstract from the reports of the Moscowian expedition to Transbaikalia in search of radium in 1914. Two great complexes of rock were found, a granite-granodiorite mass and the injected crystalline schists. The first mass is here and there intersected by lamprophyric, aplitic, and pegmatitic dikes, and there are larger aplitic masses. As the boundary between the granite and the migmatite is approached, the aplitic portions increase, until near the border there is an almost uninterrupted zone of light gray, aplitic granite. Still farther west the inclusions of crystalline schist become more numerous and the rock grades into migmatite with only occasional veins of granite. Before the intrusion of the granite, the crystalline schists were invaded by diorites and gabbros which are now metamorphosed and foliated, and cut by the later aplites and pegmatites.

The main igneous complex is called granodiorite, following Iddings, although the alkali feldspar and lime soda feldspar are in nearly equal amounts and therefore, as Eskola clearly recognizes, more rationally quartz-monzonite. The complete mode is not given. The aplitic border has a calculated mode which probably closely approximates the true composition. According to the reviewer's classification it is 227′ (new form), consequently a granodiorite-aplite, the plagioclase being almost twice as abundant as the microcline. Two types of "sviatonossite" are described, one aplitic, but otherwise the two are of practically the same composition. They contain 25–31 per cent potash feldspar, 45–48 per cent oligoclase to andesine, 9–10 per cent andradite, and 8–17 per cent aegirite-augite and accessories. The author says they are andradite-syenites, but from the proportions of potash feldspar and plagioclase the reviewer would call them andradite-syenodiorites, or, if monzonites are considered in the classification, andradite-monzonites. They fall just over the line in Family 11″ (2211″), very near 11′.

REVIEWS

The Copper Deposits of Ray and Miami, Arizona. By FREDERICK LESLIE RANSOME. U.S. Geological Survey, Professional Paper 115. Washington: Government Printing Office, 1919. Pp. 186, pl. 54, index.

The region described is about 70 miles southeast of the center of Arizona, in the mountainous district separating the plateaus of northeastern Arizona from the desert plains of the south. The Ray district lies in Pinal County; Miami is 18 miles north-northeast of Ray in Gila County, and 4 miles west of Globe, the geology of which was described by Ransome in *Professional Paper 12*.

A brief description of the earlier mining operations is followed by a bibliography and commentary. The stratigraphy of the region is then considered. The area is crossed by four ranges of hills and mountains, trending roughly northwest and southeast and separated by broad valleys which are partly structural in origin. The rock sequence comprises limestone and clastic sediments of pre-Cambrian, Cambrian, Devonian, and Carboniferous age, followed by intrusives of Mesozoic and Tertiary time, above which lie Tertiary and Quaternary clastics and lava flows. The succession does not differ markedly from that of the Globe district as presented in the work already referred to. The pre-Cambrian rocks are partly sedimentary, partly meta-igneous, as shown by chemical analysis and petrographic study. New formations are distinguished in the Cambrian, thanks to the better exposures in this area. These and the succeeding rocks are described in chronologic order, without separating the igneous rocks, as is the common custom.

Notable igneous intrusions occurred during Mesozoic times, the magmas ranging from basaltic to granitic. Andesitic extrusions of Cretaceous age are noted; no definite progressive differentiation is observed. The early Tertiary, too, was marked by acid and intermediate extrusions, and these were succeeded in turn by the deposition of conglomerates, sandstones, and flows of which the Gila conglomerate (provisionally assigned to the Pleistocene) is especially noteworthy; this formation is thought to be of alluvial origin and has a thickness of 2,500 feet; it offers attractive problems to the student of sedimentation.

A table shows the correlations of the rocks with the Grand Canyon section.

Structurally the region forms a part of the Great Basin Province. The faulting, which is especially prominent in the southerly ranges, is of the mosaic type, the displacement being normal for the most part, though thrusts are known, possibly attributable to the crowding incidental to block faulting. Excellent plates illustrate the topographic effects of homoclinal structure. Folding is, on the whole, negligible, though some of the field relations might be explained on this basis. The block faulting is supposed to be an expression of larger movements of the same sort, and the great valleys between the four ranges, the Globe Hills, the Pina-Mescal Mountains, the Dripping Springs Range, and the Tortillas, are all thought to have a tectonic rather than a purely erosive origin.

The ores of Ray and Miami are of the familiar disseminated type, the ore bodies being large and of tabular form. The metallization did not follow regular or systematic zones of fissuring, but networks of small fractures resulting from widespread disturbance of the rocks. The ore bodies are undulating, flat-lying masses of irregular horizontal outline and variable thickness, and they mostly lack sharp boundaries. The ore body constituting the east part of the Miami-Inspiration zone has a total length of 5,500 feet and a maximum width of 1,600 feet. The average thickness of the Ray ore body is estimated at 120 feet and its maximum at 400 feet. The average thickness of the Miami ore zone has not been estimated, but is somewhat greater.

The shapes of the ore bodies have been determined largely by extensive drilling, and graphs in which the copper assays of drill-hole samples from various depths are plotted, are used effectively to bring out the demarkation between the three principal zones, (1) the leached zone nearest the surface, (2) the zone of sulphide enrichment, and (3) the unenriched protore.

By far the greater part of the ore in both districts is mineralized Pinal schist; a relatively small amount is mineralized granite porphyry or quartz monzonite porphyry. Drilling at Ray has disclosed important bodies of undeveloped ore in diabase.

The principal metallic minerals of the protore are pyrite and chalcopyrite. The protore at Miami appears richer than that at Ray, the average of 126 assays under the main Miami ore body being 1.18 per cent. At Ray the copper tenor of the protore usually lies between 0.3 and 0.7 per cent.

The principal metallic mineral of the sulphide ore is chalcocite, and the average tenor of the ore thus far mined by the Ray Consolidated, 1.7 per cent copper. The average tenor of the ore sent to the Inspiration mill in 1916 was about 1.55 per cent copper.

The oxidized material is of two kinds. The first carries chrysocolla, azurite, and malachite, and is in part rich enough to ship to the smelter. Such material is relatively little iron-stained and is formed by the encroachment of oxidation in nearly pure chalcocite ore. The second type of oxidized material is leached of copper; it is *not* stained blue or green, but is mostly reddish from iron oxide. It is formed by the oxidation of material carrying considerable pyrite. No criteria were developed for recognizing capping over rich ore bodies beyond the observation that very red capping is likely to overlie protore or thin, highly pyritic ore. Assays of this sort of capping show from a trace to 0.2 per cent copper. The average thickness of the oxidized zone at Ray is 250 feet (range 45 to 600 feet).

The lower limit of oxidation and the position of the ground-water level at the time mining began were far from coincident, the divergence being particularly striking at Miami. Drill holes show that enriched ore lies partly above and partly below that water level. This suggests that enrichment was related, in important measure, to an earlier topography. This conclusion is supported by evidence which shows that much faulting has occurred subsequent to enrichment bringing oxidized and leached material in some places in lateral contact with rich ore on the same level. Rounded fragments of crushed chalcocite ore and fragments of oxidized material are found in the gouges of a number of these faults. The Pleistocene (?) Gila conglomerate appears to have been deposited subsequent to most of the enrichment, for the ores lie deepest in fault blocks capped by this conglomerate.

The deposition of the protores is attributed to thermal solutions coming from deep-lying portions of the granite-porphyry magmas, probably in early Tertiary times.

E. S. B. AND C. H. B.

Gypsum Deposits of the United States. By R. W. STONE. U.S. Geological Survey, Bull. No. 697, 1920.

This bulletin was prepared to take the place of Bulletin No. 223 published in 1904, on the same subject. Since that time (to 1918) the production of gypsum has increased more than 300 per cent. In 1918 the production was valued at $11,000,000.

Gypsum deposits are classified according to origin, mode of occurrence, relation to the earth's surface, etc.

According to mode of occurrence there are the following classes: (1) Interbedded deposits alternating with shales, limestones, and sandstones, laid down in seas or lakes. (2) Efflorescent deposits due to evaporation of water which has come to the earth's surface through gypsum deposits. The result is gypsite, a finely crystalline form of gypsum. (3) Periodic lake deposits due to deposition of gypsum from the waters of intermittent lakes. These are granular and crystalline, and vary much in size. (4) Gypsum veins due to re-working of deposits of the bedded type by ground water, and redeposition in veins. The deposits are crystalline, occurring as satinspar or selenite. (5) Gypsum dunes due to disintegration of massive gypsum or efflorescent deposits, and their transport by the wind. (6) Isoltate crystals and flakes due to formation of sulphuric acid from pyrite and the reaction of the latter on limestone.

According to origin the deposits are classified as: (1) surface-water deposits; (2) ground-water deposits.

In age gypsum deposits vary from Silurian to Quaternary. In 1918 gypsum was produced in eighteen states and in Alaska. New York was the largest producer, Iowa second, and Michigan third.

In New York gypsum has been mined more than one hundred years, during which time it is estimated that about ten million tons have been produced. The deposits are in the Salina (Silurian) formation. The gypsum is in a series of lenses and was deposited by evaporation from an inland sea. The future of the industry in this region is difficult to predict, since the gypsum beds run under younger rocks to the south and the distance they can be profitably mined is uncertain.

In Iowa there are two areas of gypsum, the area around Fort Dodge being the more important. Here the gypsum occurs in bedded deposits which overlie the Mississippian and Pennsylvanian unconformably. They are thought possibly to be Permian. These beds have been worked since 1872. At Centerville gypsum was discovered a few years ago at a depth of 500 feet, but is not yet developed. At this place the gypsum is in limestone of Mississippian age.

In Michigan the deposits are in the Michigan formation of the Mississippian system, and in the Bass Islands formation, and Salina formation of the Silurian. The gypsum is of the massive rock variety, and constitutes lenses in shale and limestone. The deposits are almost inexhaustible. The chief development is in the central part of the southern peninsula at Grand Rapids, and north of Saginaw.

In the west production of gypsum is not very great, but a number of states, especially Oklahoma, Wyoming, Utah, Nevada, California, and New Mexico have large reserves. The Wyoming deposits are found in the Embar (Permian), Chugwater (Permian or Triassic), and Spearfish (Triassic) formations. The deposits are in the Red Beds.

In California the most promising deposits are south of San Francisco Bay, associated with Tertiary and Pleistocene formations. The most valuable are of the gypsite variety. Many of them lie on the side of knobs or ridges. The deposits are due to the ground water being drawn to the surface and evaporating, leaving behind its load of gypsum acquired from the underlying rocks. There are two other forms of deposits in the California districts, intermittent lake deposits and interbedded deposits.

In New Mexico there are large deposits of gypsum which have been developed but little. They occur as bedded deposits in the Manzana group of the Pennsylvanian and in the Wingate Sandstone of the Jurassic. In the top of the latter there is a bed 100 feet thick. Gypsum also occurs as surface crusts due to evaporation at the surface, and as dunes, the material being derived from such crusts. The dunes are in the Tulurosa Desert and cover an area of 270 square miles. The gypsum from the dunes is used to a slight extent.

F. P. S.

Geology of Webster County and a Portion of Mingo District, Randolph County, South of Valley Fork of Elk River. By David B. Beger. West Virginia Geological Survey, 1920. Pp. 682, pls. 35, figs. 24, maps 2.

Webster County lies in the Cumberland Plateau, the westernmost division of the Appalachian province. The topography is characterized by deep valleys cut into an old peneplain, the relief varying from 500 to 1,000 feet. The structure is a gently southeastward dipping monocline with some minor folds. The stratigraphic range includes beds of the Upper Mississippian and Pennsylvanian. The Allegheny, and the Kanawha and New River groups of the Pottsville, form the greater part of the surface outcrops, the Monongahela having been entirely stripped off and the Conemaugh mostly. Mississippian formations, represented by the Mauch Chunk shales, of continental origin, and the Green Brier limestone, outcrop only in some of the deeper valleys of the county and in the included portion of Randolph County. The latter is remarkable for its profusion of marine forms. Devonian beds are known only from deep-well records.

The area under consideration lies to the southeast of the main proved oil and gas belt of the state. Six deep tests showed no oil and but four of them gas. It is to be noted, however, that not one of the six was drilled on a favorable structure.

Webster County, although possessing an immense amount of good coal, has but little commercial mining and no coke production. There are nineteen coal beds that appear to be workable commercially. The author estimates that the total recoverable tonnage present is about 5,144,000,000 tons.

Other minor resources include the following: (1) unutilized water power; (2) iron ore (possibly); (3) clay, not extensively utilized; (4) limestone the Hinton member of the Mauch Chunk and the Green Brier limestone; and (5) sandstone, suitable for building purposes in both the Pennsylvanian and Mauch Chunk.

The portion of the report devoted to paleontology includes some notes by W. Armstrong on invertebrate fossils from the Pottsville series. The following contributions are made:

1. "The Maximum Size of West Virginia Derbyas as Influenced by Sediments." The author concludes that the largest specimens of each species are to be found in the light-colored shales and the purer argillaceous limestones, the smallest in the fine black sediments.

2. "An Example of Shell Regeneration in Derbya crassa." This is an instance of abnormal shell growth repairing a probable break in the shell during the life of the animal.

3. "Notes on the Correlation of Certain Fossiliferous Members of the Pottsville Series." A discussion of the present uncertain status of the question is given. Some faunal lists are included.

4. "Fossiliferous Shale Beds in the Rowlesburg Section."

5. "Invertebrate Fossils Collected from the Pottsville Series of Webster County." In general the Pottsville of West Virginia shows three faunal types, a normal marine type, a restricted marine type, and a fresh-water type. Thirty-two species are listed, of which twenty-three are described and a number figured.

A. C. McF.

Bulletin No. 36, Illinois State Geological Survey. Yearbook for 1916, consisting of administrative report, and economic and geologic papers. Pp. 188, figs. 7, pls. 16, tables 33.

The report consists of four papers, the first of which is the administrative report of F. W. De Wolf, state geologist, for 1916. In Part II by N. O. Barrett, on the mineral resources of the state in 1916, the

author finds that while agriculture is the leading source of wealth, mineral industries are gradually gaining in importance. In 1916, Illinois ranked behind Pennsylvania and West Virginia only, in the total value of mineral production. It ranks first in the country in the production of fluorspar, sand and gravel, and tripoli, third in brick and tile, and coal, and fourth in petroleum, limestone, and clay products. An extensive bibliography is included.

Part III, "Clay Deposits Near Mountain Glen, Union County, Illinois," by Stuart St. Clair, describes the occurrence of a deposit of clay believed to be superior to the foreign product for the manufacture of graphite crucibles and glass pots. It is a bedded deposit, underlain by sand, and overlain by sand, gravel, and in some places by an iron-cemented conglomerate, the whole being covered by loess to varying depths. The base never has been determined by drilling. The sedimentary origin is evident. The area where it is was part of a great Cretaceous-Tertiary embayment. The existence of this deposit has been known for many years, but its development was delayed until the cutting-off of the importation of German refractory clays by the war. Four clay pits are now being worked.

Part IV, "The Structure of the La Salle Anticline," by Gilbert H. Cady. The La Salle Anticline is an asymmetric fold, extending south from La Salle to the oil fields of Crawford and Lawrence counties. It is bordered on either side by synclinal troughs, that on the east forming the northern part of the Indiana coal basin, and that on the west forming the larger and main portion of the Illinois coal fields. There are numerous minor structures. The stratigraphic section includes beds from the St. Peter sandstone through the Pennsylvanian. Several unconformities are described. These are at the base of the Chester and the Pennsylvanian, between the St. Peter sandstone and Platteville dolomite, between the Lower Magnesian limestone and the St. Peter sandstone, and several within the Pennsylvanian. The author suggests that there may be some possible relation between the anticline and the distribution of the areas of dolomization in the Platteville formation.

Two structural contour maps of the area are given. The key beds used in mapping were the top of the St. Peter sandstone and No. 2 coal of the Pennsylvanian.

A. C. McF.

The White River Badlands. By CLEOPHUS C. O'HARRA. South Dakota School of Mines, Bull. No. 13. Rapid City, 1920.

This is a useful volume on the badlands of South Dakota. It outlines the development of knowledge concerning the region, its geology,

and paleontology. The volume is abundantly illustrated and both the formations and the fossils afford excellent material for this purpose. A full bibliography enhances the value of the volume.

R. D. S.

Mineral Resources of Michigan for 1914 and Prior Years. Prepared under the direction of R. C. ALLEN. With a treatise on Michigan copper deposits by R. E. HORE. Michigan Geological and Biological Survey, Publication No. 19, 1915.

Mineral Resources of Michigan for 1917 and Prior Years. Prepared under the direction of R. C. ALLEN. Michigan Geological and Biological Survey, Publication No. 27, 1918.

These volumes were not received until late in 1920. The noteworthy feature (besides the statistics on the copper and iron industries, as well as on the non-metallic minerals) is the presence in the 1914 number of a 150-page treatise on the Michigan copper deposits, by R. E. Hore. This article serves as an excellent summary of existing knowledge on these deposits, as well as giving the author's ideas on the subject. Hore believes the native copper is essentially a primary replacement deposit from solutions (probably carrying the copper as the chloride) which accompanied and followed the extrusion of the lavas. A feature of the work is the presence of some thirty photomicrographs of polished sectons.

D J. F.

Field Methods in Petroleum Geology. By G. H. COX, C. L. DAKE, and G. A. MUILENBURG. First edition, pp. xiv+305. McGraw-Hill Book Company, Inc., 1921. $4.00.

Petroleum geologists, particularly those who are lacking in field experience, will welcome this book. It treats chiefly of the recognition of structural features favorable for the accumulation of petroleum, and of map-making and the instruments used in making maps. It includes the solution of geologic problems and the making of a geologic report. Problems of a "resident geologist" are not included. Graphic solutions of geologic problems are also omitted. It is assumed that the reader has a knowledge of the fundamental principles of geology and mathematics, including trigonometry.

Chapter I contains a description of the large variety of instruments used by geologists, and Chapter II outlines instrumental methods in

general use. Chapters III and IV include a discussion of the surface features which lead to the identification of strata and structural conditions; the methods of obtaining and recording geologic data; also the actual field procedure from the selection of the field party to the preparation of the final reconnaissance or detailed report.

The statement is made (p. 129) that "the field work of a petroleum geologist is . . . . made up largely of a search for anticlines and terraces, and of mapping such areas." This statement would have been more nearly correct a few years ago.

The book contains a glossary of about four hundred words, such as: Algonkian, Carboniferous, Cenozoic, Contours, Dip Slope, Orientation Rod, Stadia, Sedimentation, Volcanic Ash. There is also an appendix containing tables of natural functions, reductions of stadia observations for rod readings of 100, stadia tables for obtaining differences of elevations, gradienter table (Stebbinger drum) for determining distances, and a number of other tables, including barometric corrections.

A limp leather binding and pocket size make the book convenient for field use.

W. O. G.

Lithologic Subsurface Correlation in the "Bend Series" of North Central Texas. By Marcus I. Goldman. U.S. Geological Survey, Professional Paper 129 A, 1921, Govt. Printing Office, Washington. Pp. 22, pl. 1, fig. 1.

Since the early work of Hatch, the micro-petrology of sediments remained a rather neglected field to which the physiographer has only turned now and then in the exceptional instances when there was a question whether a certain sand was wind- or water-laid, a field almost wholly ignored by the stratigrapher. Now the subsurface lithologic correlations in oil fields have assumed economic importance, however, interest in the long-neglected subject is revived, and geologists are glad to learn of the establishment by the U.S. Geological Survey of a laboratory devoted to the study of sediments. The paper here reviewed represents an invaluable addition to the technology of petrographic correlation from well logs and well samples.

The problem presented was the correlation of sediments thought to be the equivalents of the Smithwick and Marble Falls beds and of a part of the Strawn formation of Pennsylvanian age, as well as of the Lower Bend Series (Mississippian) in north central Texas. The method employed was much like that outlined by Trager (*Econ. Geol.*, XV, 1920);

the more exact scheme of analysis described by Trager, however, was not resorted to. Depths from the surface are plotted as ordinates in ten-foot units and the composition in percentage of argillaceous, arenaceous, flinty, and calcareous sediments, as determined from the log samples, are the abscissae; the diagram thus constructed is essentially a graphic columnar section. Correlation is based on the relative increase or decrease of one type of sediment, rather than on the absolute percentage composition of the bed in question. A mere glance at the plate given serves best to illustrate the method used. Flinty sediments are taken to be equivalents of calcareous deposits, since the conditions under which they originally formed are similar.

Such ratios established a generalized sequence for the counties of Comanche and Palo Pinto (and probably also Eastland and Stephens, the intervening counties). This sequence follows:

<table>
<tr><td rowspan="6">Pennsylvanian</td><td>Strawn formation</td><td rowspan="4">=True Smithwick shale</td></tr>
<tr><td>True "Upper Smithwick" shale</td></tr>
<tr><td>"Smithwick lime"</td></tr>
<tr><td>"Lower Smithwick shale" of the Ranger field</td></tr>
<tr><td>"Black lime" of the Ranger field</td><td rowspan="2">=True Marble Falls limestone</td></tr>
<tr><td>A succession of limestones and sandy limestones, hitherto unnamed</td></tr>
<tr><td rowspan="2">Mississippian</td><td>Lower Bend limestone</td><td></td></tr>
<tr><td>Lower Bend shale</td><td></td></tr>
</table>

Unconformity

Ordovician—Ellenburger limestone

The entire Pennsylvanian and Mississippian (including the lower part of the Strawn) has an average thickness of 1,100 feet.

No marked unconformities are reported above that which separates the Ordovician and Mississippian, though eleven disconformities of varying importance, not indicated above, are recognized. Several are intraformational. In the case of the disconformities, glauconite and phosphate nodules in some cases mark the plane of separation. These glauconite grains are coarser and less rounded than those of the thick greensands of other horizons and resemble more closely those of the New Jersey Cretaceous. The occurrence of sulphides at the horizons marking ' akinetic" surfaces of maximum base-leveling is another noteworthy feature.

Many other interesting facts are discussed, and points of considerable theoretical significance are brought forward—such as the source of

the oil in the north central Texas region, the northeastern source of the Bend sediments, and the very great trustworthiness of lithologic correlation in regions where faunas change slowly and sediments accumulate rapidly.

The one disappointment felt by the reviewer was due to the lack of explicitness in dealing with the technology of examinations. For novices a careful outline of the things to be sought for in making lithologic subsurface correlations would be helpful.

C. H. B., Jr.

Report on Mining Operations in the Province of Quebec, 1919. Province of Quebec, Canada, Bureau of Mines, 1920. Pp. 160.

The phenomenal growth in the mineral industries of Quebec is evidenced by the increase in the value of her annual mineral output from two and a half million dollars in 1900 to nearly twenty-one million dollars in 1919.

While metals contribute to some degree to this output, Quebec's most important resources are non-metallic—asbestos and building-materials dominating.

Asbestos is to be credited with over half of the total mineral output by value in 1919, the mines of Quebec constituting the world's principal source of this mineral. The United States is very directly interested in this Canadian industry because about 89 per cent of the output comes to the United States, mainly in an unmanufactured state, and is there fabricated for use in the United States and for shipment abroad. Some 3 per cent of the Canadian output is exported directly to England and the remainder to various other countries of Europe and to Japan.

The magnesite industry of Quebec, which came into prominence with the cutting off of the German and Austrian imports during the war, declined in 1919 to less than half the 1918 tonnage.

E. S. B.

Deposits of Iron Ore near Stanford, Montana. By L. G. Westgate. U.S. Geological Survey, Bull. 715-F, 1920. Pp. 85–92.

This report describes several bodies of low phosphorus-hematite ore in the northern part of the Little Belt Mountains. The deposits are as yet undeveloped. Tonnages at two of the best showings are roughly estimated at one and one and one-third million tons respectively.

The main facts of the occurrence and character of the ore and the associated rocks are as follows:

1. The iron ore occurs in tabular bodies at the contact of the porphyry and the Madison limestone. The ore bodies range in width from 5 to 60 feet, and average about 20 feet.

2. The ore is the result of the replacement of the limestone, as shown by its much more uneven contact surface against the limestone and by the retention here and there in the ore body of the banding of the limestone and of parts of the limestone itself.

3. Where the contact is inclined the hematite is more commonly found where the limestone is the footwall.

4. The ore is a compact gray or reddish-gray hematite. It contains in places enough magnetite to make it react to the magnet. It is not to any large degree limonitic at the surface. At the one point where any considerable depth has been reached (125 feet, on the Snowbird claim) the ore contains a little pyrite and chalcopyrite.

The limestone at the contact with the porphyry is usually altered to a yellowish, finely crystalline marble. No contact silicates were seen except a small amount of wollastonite in the rock taken from the tunnel on the Snowbird claim [pp. 90 and 91].

E. S. B.

Gypsum in 1919. By R. W. STONE. Mineral Resources of the United States, 1919. Part II, pp. 99–113.

The gypsum industry in 1919 showed a slight recovery from the low level of production touched in 1918. The report gives the usual statistical data, the only unusual feature being a discussion by Dr. William Crocker, professor of plant physiology at the University of Chicago, of "Agricultural Gypsum and Its Uses."

Eighty years ago land plaster was one of the most used of fertilizers, and there are indications that it will again come into general use.

There are four main uses of this substance in agriculture: As a source of sulphur for alfalfa, red clover, or other crops of high sulphur requirement, and for combination with ground-rock phosphate as a substitute for acid phosphate; as a preserver of manure; as a soil stimulant; and as an amendment for black alkali [p. 109].

E. S. B.

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A SEMI-QUARTERLY

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Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Because of the high cost of printing, this Journal has found it necessary to adopt the following rules: ¶ 1. If articles exceeding 25 pages in length are accepted for publication in the Journal, the cost of composition *beyond 25 pages* shall be paid by the author or by the institution which he represents. at the current rates of the University Press. ¶ 2. The cost of illustrative material, in excess of $1.00 per page for the article, beyond the cost of type which would have occupied the same space, shall be borne by the author. ¶ 3. The cost of corrections in proof in excess of 10 per cent of the cost of first composition, will be charged to the author. ¶ 4. While the cost of printing remains as now, the Journal cannot supply reprints without charge, but reprints will be furnished authors at cost, if ordered in advance of publication.

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

The Early Pre-Cambrian Formations of Northern Ontario and Northern Manitoba. By E. L. Bruce.

The Hot Water Supply of the Hot Springs, Arkansas. By Kirk Bryan.

The Time of Glacial Loess Accumulation in Its Relation to the Climatic Implications of the Great Loess Deposits: Did the Loess Chiefly Accumulate during Glacial Retreat? By Stephen S. Visher.

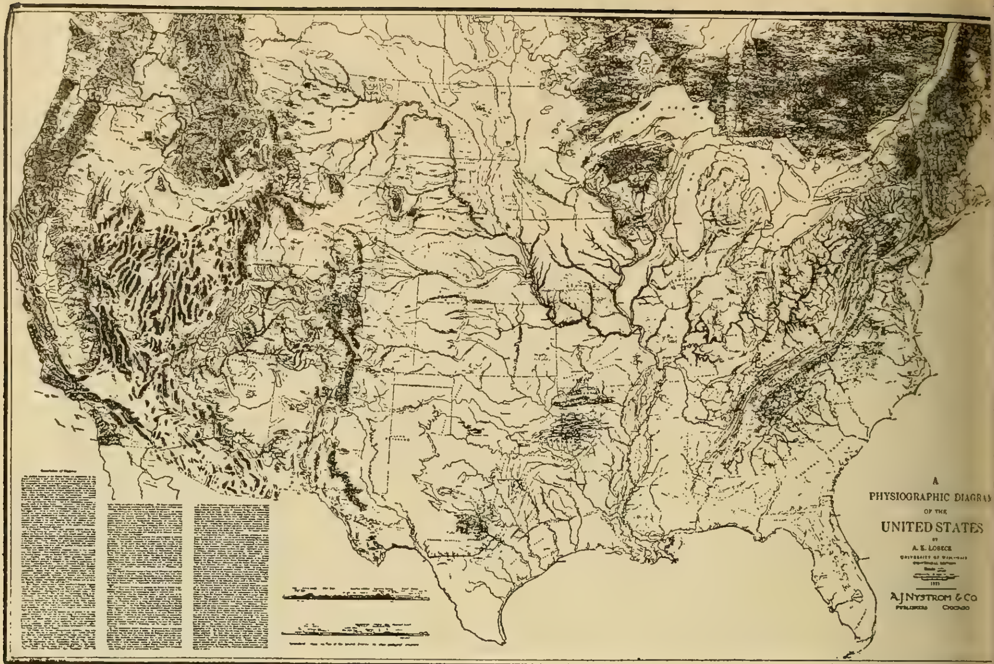
The Problems of the Anorthosites and Other Monomineral Igneous Rocks. By F. Loewinson-Lessing.

A Devonian Outlier near the Crest of the Ozark Uplift. By Josiah Bridge and B. E. Charles.

The Nephelite Syenite and Nephelite Porphyry of Beemervill, New Jersey. By M. Aurousseau and Henry S. Washington.

The Lava Field of the Parana Basin, South America. By Charles Laurence Baker.

The Behavior of Inclusions in Igneous Magmas. By N. L. Bowen.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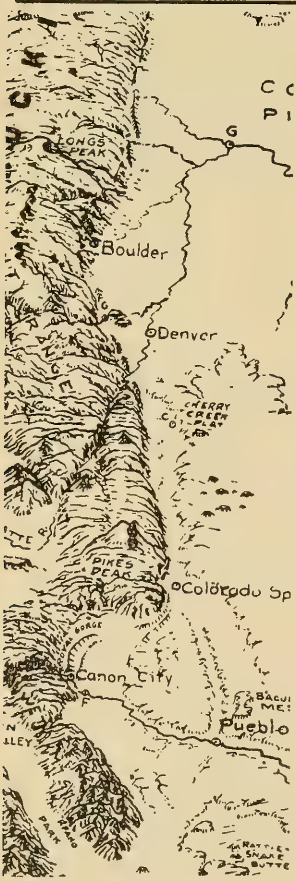
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July-August 1922

POST-GLACIAL LAKES IN THE MACKENZIE RIVER BASIN, NORTH WEST TERRITORIES, CANADA

A. E. CAMERON
University of Alberta, Edmonton, Alberta, Canada

It is a well-known fact that lakes or ponds of impounded water would form whenever the retreating continental ice sheet receded down a stream valley. It is therefore evident that the run-off from the eastward slopes of the Rocky Mountain cordillera would be impounded behind the retreating ice front of the Keewatin glacier as it receded, and the lakes so formed would expand laterally along the margin of the ice sheet, and the water would collect both from the inflowing streams and the melting ice until it rose above the lowest point in the stream valley walls, when it would spill over and form a new river course, possibly at considerable variance to the pre-established drainage lines. Thus we would expect to find evidence of ice-dammed lakes of greater or less magnitude throughout large areas in the northern portions of the great plains area of the Dominion of Canada. It is not the object of this paper to deal with the possible extent of such lakes throughout the northern regions, but rather to consider one or two specific stages in the lake expansions as they were apparently developed in the lower Peace and Athabaska river valleys, Athabaska Lake and Great Slave Lake.

The area to be discussed is shown in the accompanying map (Fig. 1). It lies between latitudes 56° north and 63° north, longitudes 107° west and 120° west, and it comprises the lower portions of the valleys of Peace and Athabaska rivers, Athabaska Lake and Great Slave Lake.

Tyrrell,[1] in his report on Athabaska Lake and Churchill River, makes frequent reference to the great post-glacial lakes of this region. He says:

> North of the watershed between Churchill and Stone rivers, most of the akes appear to have stood at a higher level than they do at present, in the time immediately subsequent to the retirement of the great ice-sheet. The natural inference is that they lay between the face of the waning ice-sheet and higher land over which the water flowed to form the great rivers of the glacial period.

He proposed the addition of the prefix "hyper-" to the name of the present lake or river to designate the former high-level lake that occupied its basin or valley.

Tyrrell's report covers the area east of Athabaska River and south of Athabaska Lake, and is therefore in part included in the region under discussion. Certain parts of his reports are of prime importance in any consideration of the question. Particular reference must be made to his Hyper-Black Lake, Hyper-Athabaska Lake, and Hyper-Churchill Lake. Black Lake lies directly east of the eastern extremity of Athabaska Lake and is connected with Athabaska Lake by a broad, trenchlike valley at present occupied by Stone River. Tyrrell says:

> Hyper-Black Lake stood 125 feet above the present level of Black Lake, and extended for a long distance up Cree and Stone rivers. Hyper-Athabasca Lake rose above the present level of Lake Athabasca, as is shown by the beautiful raised beaches on Beaver-lodge Island, and the wide sandy plains seen by Mr. Dowling on William River; but whether it at any time was confluent with Hyper-Black Lake was not determined. . . . . Hyper-Churchill Lake lay in the present valley of Churchill River, and, when at its greatest height, seems to have extended southward as far as the sand-hills around Clearwater Lake on the Green Lake trail.

[1] J. B. Tyrrell, "Athabasca Lake and Churchill River," G.S.C. *Annual Report*, New Series, Vol. VII, "D," 1895.

From a perusal of Tyrrell's report it is possible to outline at least one main drainage channel of the great post-glacial lakes that is of particular importance to our problem.

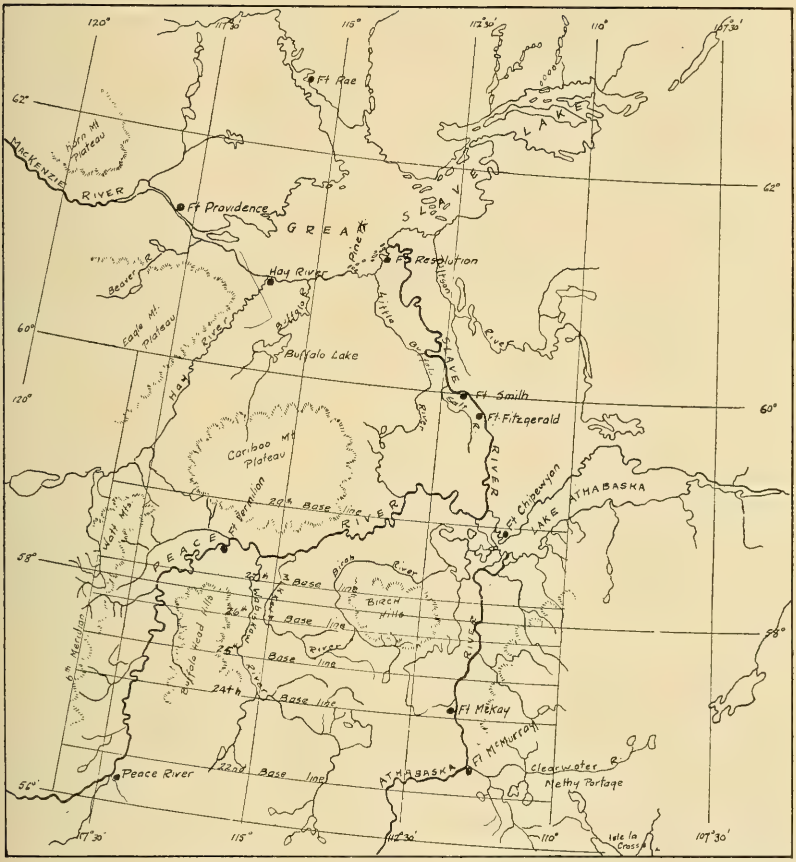

FIG. 1.—Map of portion of Mackenzie River basin, showing lower portions of Peace and Athabaska river valleys and basins of Athabaska Lake and Great Slave Lake. Scale, 1 inch = 117 miles.

This channel appears to connect with the Clearwater River valley at Methy portage, following it southeast through Buffalo Lake, Isle la Crosse Lake, Beaver River, Green Lake, Big River, and Shell Creek to the valley of the Saskatchewan. It is reported as a broad, trenchlike valley with the watershed between the Saskatche-

wan and Churchill rivers lying in a sandy plain at the bottom of the deep valley. As will be shown later, a portion of this valley probably at one time was the principal drainage channel of great post-glacial lakes lying in the Athabaska and Peace river valleys, though possibly Hyper-Churchill Lake intervened to take the waters from Hyper-Athabaska Lake before discharging them into the Saskatchewan River.

A second channel is suggested in his account of the east end of Athabaska Lake and the valley of Stone River below Black Lake. This appears as a short, narrow channel connecting the waters of Hyper-Athabaska Lake with those of Hyper-Black Lake. It would seem very probable that during a certain period of the lake formations these two bodies of water were confluent by way of this channel, and that the outlet of the chain of lakes lay possibly by way of Mudjatick River Valley to Hyper-Churchill Lake or by another channel farther east.

Just at the eastern end of Athabaska Lake Tyrrell reports two distinct sets of glacial striae: an earlier one tending south, 65° west, parallel to other striae seen almost everywhere along the shore and doubtless made by the ice sheet from the northeast; and a later one, tending south, 35° west, probably made by a local glacier descending from the high land to the north after the greater ice sheet had withdrawn.

A portion of the moraine of this later local glacier may be seen as a great stretch of huge broken masses of rock, forming a prominent point, and covering the shore for a considerable distance beyond it. . . . . Athabasca Lake is here five miles wide, and lies in a long narrow valley with a steep sandstone escarpment between 400 and 500 feet high on its south side. The later glacier from the north flowed into the valley at this point, and probably reached across to the south side, completely filling it and damming up the water from the east to the height of the sandstone plain on the south, which is at about the level of the high benches previously described on the banks of Cree River and along the west shore of Black Lake. The occurrence of an ice dam across the valley accounts fully for the former existence of a large lake in the present basin of Black Lake. Without the ice dam, or some other dam of which no evidence can be found, the water of Black Lake could not have stood much above its present level in glacial or post-glacial times, for the great valley of Athabasca Lake, which extends eastward to Black Lake, dates back to a period long before the glacial epoch.

The formation of this dam is important in the consideration of the drainage of the great lakes formed in the Athabaska and Peace river valleys to the west. Tyrrell does not seem to appreciate the fact that for a long period the northward drainage of the Athabaska Lake Valley was blocked, and that consequently the waters of Hyper-Athabaska Lake must have stood high and the natural outlet of these waters would, at one time at least, be by way of Black Lake and the Stone River Valley; and, therefore, the damming would probably have more to do with the closing of a possible outlet of Hyper-Athabaska Lake than the formation of a Hyper-Black Lake. As has been already suggested, the writer believes this damming separated the confluent waters of Hyper-Athabaska and Hyper-Black lakes, allowing the rapid drainage of the smaller Hyper-Black Lake eastward, while the water still remained high in Hyper-Athabaska Lake.

PEACE RIVER VALLEY

If one stands on the plain level above the town of Peace River, an extended view both up and down the valley of the Peace is available. The strikingly flat character of the plain level is apparent, and, if one could extend his vision, he would be struck by the similarity of elevation between the level on which he stands and that of the high lands lying to the north and the east. The elevation of the plain at Peace River is 2,250 feet above sea-level. That of the Watt Mountains is about 2,700 feet, and that of the Eagle Mountains is about the same. Caribou Mountain Plateau is slightly higher. The summit on the twenty-ninth base line is 3,225 feet, and to the northward the elevations probably average over 3,500 feet. Buffalo Head Hills and the Birch Hills average about 2,700 feet, and the plain level at the end of steel on the Alberta and Great Waterways, sixteen miles from McMurray, is 2,500 feet. This similarity of elevation is conspicuous, and can only point to the fact that these present outlying plateaux were in recent geological times connected and formed a continuous plain of fairly uniform relief.

At Peace River, the valley of the Peace is both broad and deep, and yet it is evidently well filled by the river it contains. Here

is no river flowing sluggishly in a valley much too large for itself, but a mighty stream which, still in its youth, has carved and is still carving a valley in just proportion to its size.

On descending the river below the town, the valley walls contract to gorgelike proportions, and the apparent crest of the valley gradually lowers. Ascending to the crest at a point some 50 miles below Peace River, one would find himself on another plain level at a lower elevation than that above Peace River town.

The plain is narrowed to a width of about 50 miles, but is distinctly flat. It is bordered on the east by the shoulder of Buffalo Head Hills, and on the west by a southerly extension of the Watt Mountain Plateau. The elevation of this plain is about 1,600 feet.

Descending the river still farther to a point near Battle River and there scaling the immediate valley walls, another plain level confronts the eye on reaching the top, this time at an elevation of 1,100 feet. East or west from the river this plain stretches some thirty to forty miles before rising gradually to a comparatively narrow bench land at an elevation of about 1,600 feet which must be crossed before ascent can be made to the old, original plain level.

About 50 miles above Vermilion the Peace River swings rapidly eastward and, the valley walls receding, it enters a widely extended plain area at an elevation of about 800 feet which, at Vermilion, stands scarcely more than 30 feet above water level. This plain level is practically continuous with the basin of Athabaska Lake and extends northward around the foot of Caribou Mountain Plateau to the basin of the Great Slave Lake.

WABISKAW AND ATHABASKA RIVERS

Strikingly similar features to those outlined above are to be found in the valleys of the Wabiskaw and Athabaska rivers to the east. These are well brought out in the profiles of the base, lines and meridians of the Dominion Topographical Surveys as shown in the accompanying sketches (Fig. 2).

The 1,600-foot level shows as the broad plain south of Hay River on the sixth meridian; distinctly on the shoulder of Caribou Mountains on the twenty-ninth base line; on both slopes of Birch Hills on the twenty-seventh base line; on both sides of the

valleys of the Peace and Wabiskaw rivers on the twenty-sixth; on the Peace, Athabaska, and Wabiskaw valleys on the twenty-fifth; slightly on the Peace and Athabaska rivers on the twenty-fourth base line and just faintly on the east side of the Athabaska River on the twenty-second base line.

The 1,100-foot level shows on the northern half of the broad plain of Hay River on the sixth meridian; throughout the greater

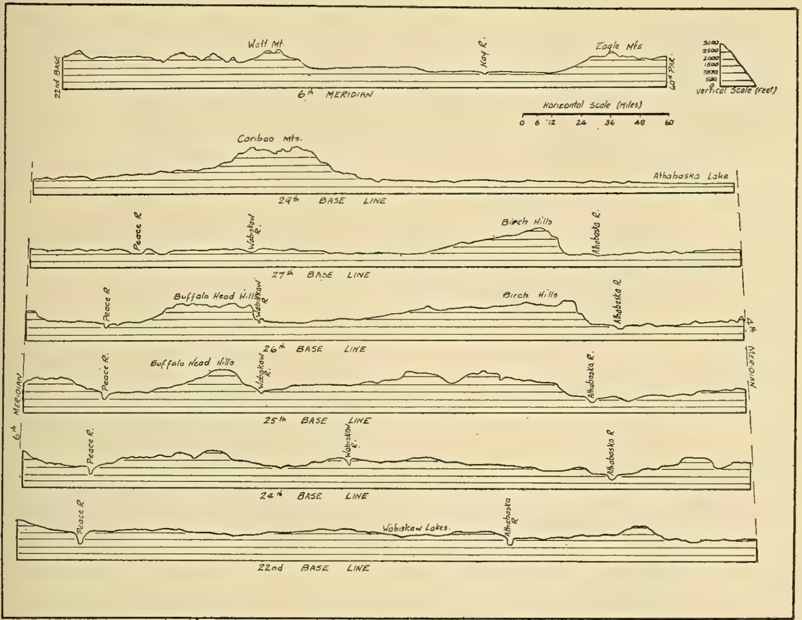

FIG. 2.—Profiles of base lines and meridians of the Dominion Topographical Surveys, Department of Interior.

part of the twenty-seventh base line; somewhat on the Peace River and very pronouncedly on the Athabaska River on the twenty-sixth base line; and on the Athabaska River only on the twenty-fifth base line.

The 800-foot level shows between the fourth and fifth meridians on the twenty-ninth base line; and in two places on the twenty-seventh base line—the valley of Athabaska River, and near the fifth meridian.

HAY AND BUFFALO RIVERS

A trail leads overland from Vermilion, on Peace River, to Hay River. For about 80 miles northwest from Vermilion it traverses a flat plain at an elevation of about 800 feet above sea-level. It then crosses a low divide, the summit being at 1,500 feet, and enters the long, narrow plain area in the center of which flows Hay River. The elevation of this plain at its upper end is about 1,100 feet. Hay River follows this plain in a northeasterly direction for 150 miles, dropping scarcely more than two feet to the mile, until, within 50 miles of its mouth, it falls abruptly over an escarpment into the basin of Great Slave Lake, forming Alexandra Falls (Figs. 3 and 4).

FIG. 3.—View of Alexandra Falls, Hay River, N.W.T., looking upstream. (Photo by A. E. Cameron, 1916.)

SLAVE RIVER

At Fort Smith the Slave River cuts through a poorly developed escarpment some 125 feet high. The crest of the escarpment shows distinct evidence of the shore-line conditions in the form of well-developed sand dunes and a flat horizon to the north and east. West of Fort Smith at

FIG. 4.—View of Alexandra Falls, Hay River, N.W.T., showing close view of escarpment. (Photo by A. E. Cameron, 1916.)

Salt River an abandoned lake basin is distinctly shown in the salt plains lying at the foot of an escarpment facing east (Figs. 5 and 6). The plains are for the most part void of vegetation and form a broad flat, water-soaked in the wet season and salt-incrusted in the dry. Shore-line conditions are shown by narrow spruce- and

FIG. 5.—View of the salt plains on Salt River, west of Fort Smith, N.W.T. (Photo by A. E. Cameron, 1920.)

FIG. 6.—Another view of the salt plains on Salt River, west of Fort Smith, N.W.T. (Photo by R. T. Hollies, 1920.)

poplar-clad points jutting out from the irregular face of the escarpment into the clay flats, bordered frequently by bowlder pavements or shingle beaches. Low off-shore islands showing water-deposited material are also noticeable (Fig. 7). The Salt River escarpment

follows north down the west side of Little Buffalo River for about 30 miles and then gradually disappears to the west.

GREAT SLAVE LAKE

Great Slave Lake lies at an elevation of about 500 feet above sea level. The south shore of the lake near Pine Point, west of

FIG. 7.—Small island in salt plains, west of Fort Smith. Salt spring deposits in foreground. (Photo by A. E. Cameron, 1920.)

FIG. 8.—Wave-cut limestone bluff at elevation of 200 feet above Great Slave Lake. (Photo by R. T. Hollies, 1920.)

Resolution, rises rather steeply for a few miles, showing storm-built beaches of limestone shingle, to a limestone bluff at an elevation of about 700 feet (Fig. 8). Inland lies a rolling country which rises gradually to the south. Each roll shows limestone shingle beaches and bowlder pavements, and not a few are topped by sand dunes.

Each roll may be traced eastward to where it pinches out into the hollows between. The trend of these rolls conforms closely with the direction of ice movement as established by glacial striae at various points along the lake shore. Each roll can only represent a point, carved out by the glacier when it was excavating the basin, around which the waters of the lake lapped at some stage in its development.

FIG. 9.—View of shingle beach, at elevations up to 150 feet above present lake level, Great Slave Lake, N.W.T. (Photo by A. E. Cameron, 1916.)

FIG. 10.—View of shingle beach, at elevations up to 150 feet above present lake level, Great Slave Lake, N.W.T. (Photo by R. T. Hollies, 1920.)

Elsewhere about the lake shores undoubted lake beaches and wavecut cliffs are observable at various elevations above the present lake level. They are very numerous and excellently well developed, and are noticeable wherever high land exists in the vicinity of the present shore line (Figs. 9 and 10).

TERMINAL MORAINES

In the valleys of Hay and Buffalo rivers occur terminal moraines, marking positions of the ice front during stages of halt or of slight

re-advance of the ice sheet during the general retreat from the region. The moraines consist of low ranges of irregularly shaped hills, somewhat higher in elevation than the adjacent country, and trend in a general direction at right angles to the movement of the glacier, as shown by glacial striae. The best-developed moraine occurs immediately north of Buffalo Lake. The morainic hills here have an elevation of 200 to 300 feet above the surrounding country, and form a dam behind which the waters draining from the north slopes of Caribou Mountains are ponded, forming the large shallow body of water known as Buffalo Lake. This moraine extends north to within a few miles of Great Slave Lake. Two moraines were noted in the valley of Hay River; one tending to connect the Watt Mountain Plateau with that of Eagle Mountains; and the other, the Caribou Mountains with Eagle Mountains. The low ridge of glacial drift now existing between Watt and Caribou mountains and forming the present watershed between Peace and Hay rivers appears to be an interlobate moraine formed between two lobes of the waning glacier.

PROBABLE LAKE EXPANSIONS

From this somewhat scanty evidence an attempt may be made to outline the various stages of lake formations developed as the continental ice sheet retreated from the region.

At least three definite glacial lobes are apparent in the area. One extended up the valley of Hay River; a second swung west, south of the Caribou Mountains, and probably sent tongues up the valleys of the Peace and Wabiskaw rivers; while the third lay in the basin of Athabaska Lake with its tongue pointing up the valley of Athabaska River.

The first stage to be considered (Fig. 11), is when the water level stood at about 1,600 feet. The Hay River lobe extended up the valley to a point south of the sixtieth parallel. The edge of the other lobes is not determinable from the information at hand, but it would appear that the Peace River lobe extended well up toward Vermilion and probably sent a tongue south up the valley of the Wabiskaw to a point close to the twenty-sixth base line; while the Athabaska lobe must have extended at least as far south as this same line. The similarity of elevation of the lake benches

in all the valleys can only point to the fact that the waters were in conjunction with one another. Those in the Hay and Peace river valleys undoubtedly were connected through straits between Caribou Mountains and Watt Mountains. The other connections were apparently by marginal channels along the ice front. Drainage northward by way of the Mackenzie River was blocked, and it

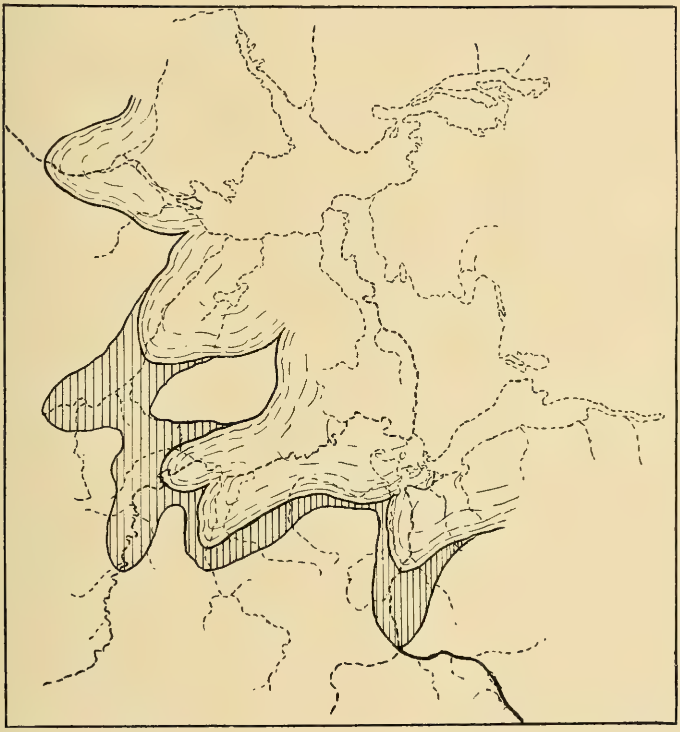

FIG. 11.—Outline map showing probable position of Keewatin ice sheet and lake expansions when the water stood at the 1,600 foot level.

seems likely that the lake in the Athabaska Valley was somewhat lower in level than the others, and may have been drained eastward toward Hudson's Bay. The more probable outlet, however, was by way of the Clearwater River and Methy portage to the Churchill River Valley. The summit of Methy portage is 1,735 feet above sea-level—scarcely more than 200 feet higher than the lake level at that stage. This difference could easily be accounted for by

differential elevation of the land following the retreat of the ice front.

In the second stage (Fig. 12) the water level stood at about 1,100 feet. The Hay River ice had retreated to the morainal ridge north of Buffalo Lake and the Peace and Athabaska lobes had similarly retreated. Drainage down the Mackenzie was

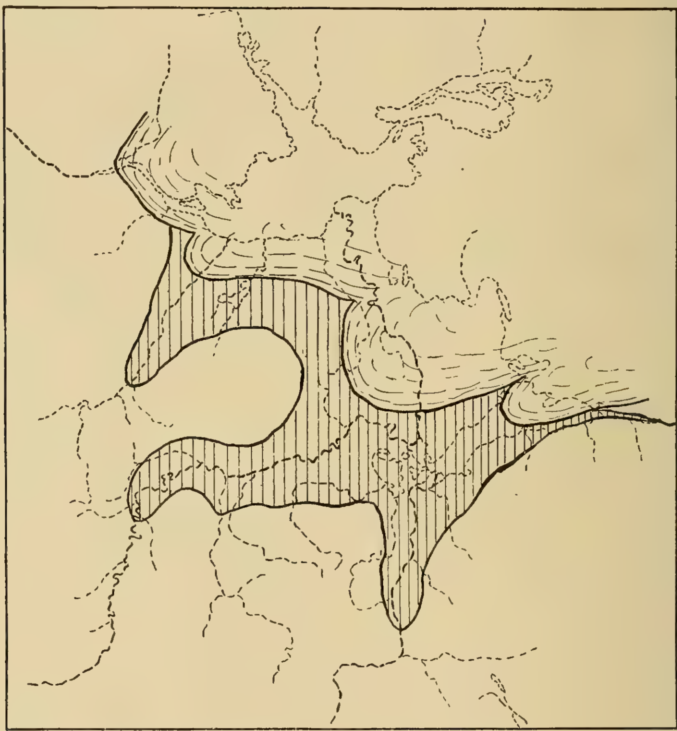

FIG. 12.—Outline map showing probable position of Keewatin ice sheet and lake expansions when the water stood at about the 1,100 foot level.

still blocked, the lake basins were all continuous, and outlet must have been by way of Fond du Lac on Athabaska Lake, in the long, extended arm of that lake, and thus eastward, probably by way of Churchill River.

The Mackenzie River outlet must have been cleared soon after, but was apparently blocked farther north, for we find the water level standing at 800 feet and developing beaches on all sides of

the present shore line. At the 800-foot elevation (Fig. 13) the ice had receded clear of Athabaska Lake and practically clear of Great Slave Lake, though a small tongue remnant of the Great Slave Lake lobe may have occupied the eastern extension of the lake. The water level was well below the Fond du Lac outlet on Athabaska Lake, but the Mackenzie Valley was open and drainage

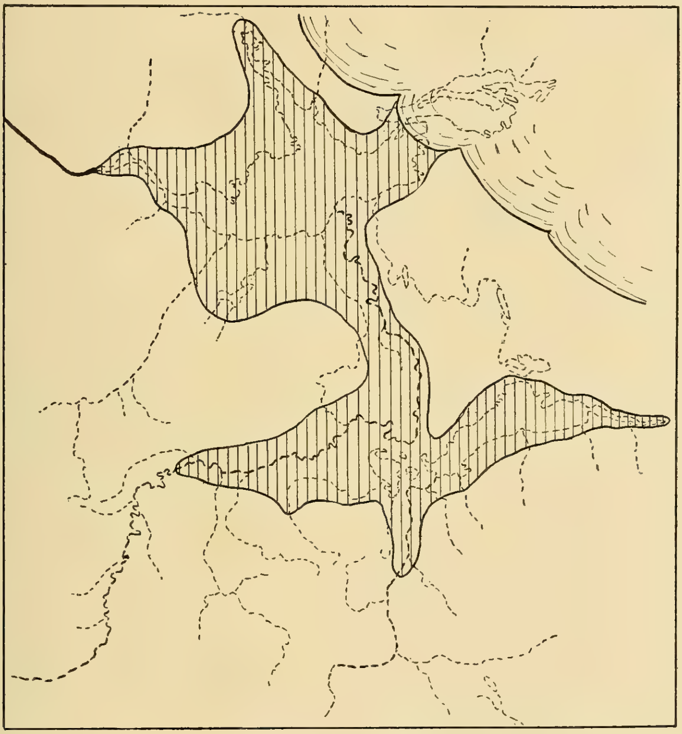

FIG. 13.—Outline map showing probable position of Keewatin ice sheet and lake expansions when the water stood at about the 800 foot level.

should have been that way. The two main basins are continuous by means of a narrow strait across the low escarpment at Smith. The Great Slave Lake basin was expanded to take in the present basin of Buffalo Lake, though probably low morainal islands marked the position of the morainal ridge north of Buffalo Lake.

On the retreat of the ice, isostatic readjustment of the land areas took place, with a raising of the land in a series of differential

elevations to the north and east, possibly on successive hinge lines. The area south of McMurray was probably differentially raised, causing elevation of the Methy portage outlet, and, later, movements developed in the neighborhood of Fort Smith, raising a land barrier there about 125 feet high, and causing a separation of the two basins (Fig. 14). We thus find two large bodies of

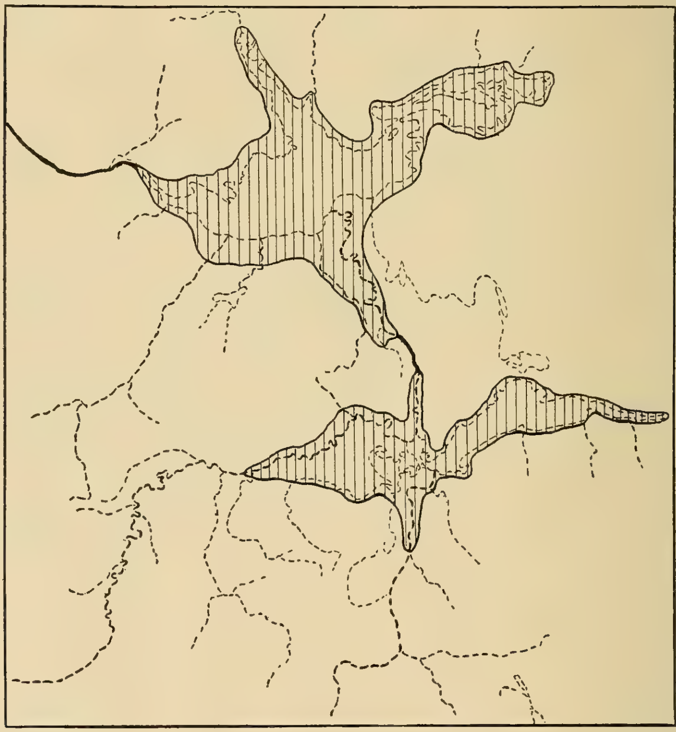

FIG. 14.—Outline map showing probable lake expansion when water stood at the 700 foot level.

water existing in the separated basins: Athabaska Lake, standing at about 750 feet, and Great Slave Lake at some 600 feet.

The two basins have acted very differently since their separation. Isostatic readjustment north of Athabaska Lake has tended to close the outlet, keeping the waters ponded back, and drainage has been accomplished by Slave River cutting its channel as fast as the ground rose. As a consequence the water level has dropped

only slightly since that time. The level of Athabaska Lake is now 699 feet above sea-level at average water conditions.

Northward, however, conditions are very different. The outlet of the basin lies at its western corner, and differential elevation to the north and east has only had the effect of spilling more water down the Mackenzie River, with the result that the basin has been rapidly drained. The rapidity with which the water level fell on Great Slave Lake is excellently well shown in the storm or seasonal beaches found on the forelands, particularly along the north shore. At one place on Windy point over 100 such beaches are observable in an elevation of some 250 feet, and the crest of the hill is marked by a horseshoe beach developed as the ground rose above the water level. The beaches are of fairly uniform depth, and throughout most of the rise occur as a series of very regular waves, indicating that elevation has been at a constant, uniform rate. That movement is still going on is apparent from the beach lines built up in recent times.

In conclusion, the writer can only admit that these are wide generalities based on very insufficient data, and undoubtedly will bear much correction. He feels sure, however, that the outlines suggested are at least approximately correct. Much work has yet to be done, and detail work on the problem would yield many points of scientific interest. One main problem that presents itself is the study of the Great Slave Lake shore lines with a view to determining the time period since the last glacial age. Dr. A. P. Coleman produced[1] much interesting information on this subject by a detail study of raised beaches, delta deposits, and lake bars on Lake Ontario. The seasonal beaches of Great Slave Lake, studied in detail, would give similar information. The Alexandra Falls on Hay River have receded 6.5 miles since their original development—a distance almost equal to that of Niagara Falls. Slave River has completely filled up the long, southward-extending arm of Great Slave Lake, and is still building rapidly into the present lake. The rate at which alluviation is taking place could be readily determined, and an excellent time record seems available.

December, 1921

[1] A. P. Coleman, *Proceedings of the International Geological Congress, Toronto, Canada, 1913*.

DINOSAUR TRACKS IN HAMILTON COUNTY, TEXAS

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Dallas, Texas

Attention has been called by E. W. Shuler to the occurrence of dinosaur tracks in the Glen Rose limestone of Lower Cretaceous age, near the town of Glen Rose, Somervell County, Texas.[1] Another interesting occurrence of similar tracks has recently come to light in the extreme southern portion of Hamilton County, Texas, about sixty miles south-southwest of the first-mentioned locality (Fig. 1).

The tracks in Hamilton County are also in limestone belonging to the Glen Rose formation. They are exposed in the bed of Cottonwood Creek (Fig. 2), a small headward tributary of Lampasas River, and are confined to a single stratum of rather soft, compact, yellowish limestone about a foot thick, which for a distance of probably 800 feet makes the bed of the creek. In the Glen Rose locality the tracks were evidently made by one individual moving continuously in the same direction; but in Hamilton County they were made by a number of individuals, and the tracks point in every direction of the compass, this spot seemingly having been a favorite haunt of dinosaurs of every size and presumably, also, of every age.

The examination upon which these notes are based was made hurriedly and without adequate means properly to clear the creek bed of the accumulated débris. Normally this portion of the bed of Cottonwood Creek is covered with several feet of water, but the unusually dry summer season of the past year offered a favorable opportunity to examine the footprints, since the creek was free from running water; but it developed that cattle which frequent the water holes along the creek had worked down shale and gravel from the banks in such quantities that almost the entire surface

[1] *Amer. Jour. Sci.*, Vol. XLIV (October, 1917), pp. 294–98.

of the rock was covered with mud or sun-baked soil to a depth varying from several inches to as many feet. It was therefore impossible to clean off the rock over more than limited areas in the short time available.

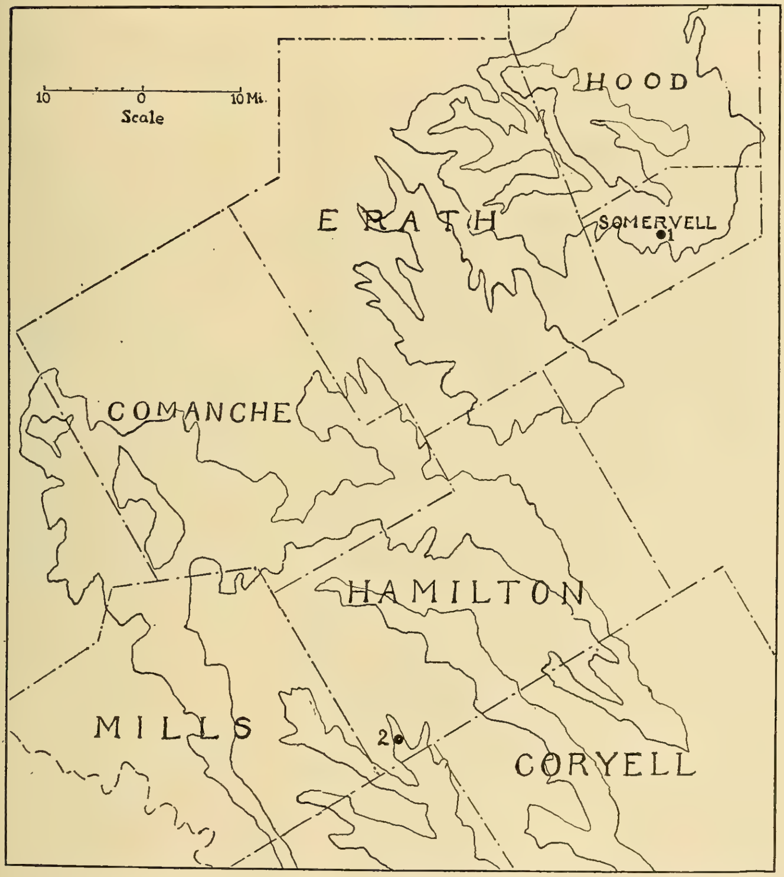


FIG. 1.—Sketch map of a portion of Central Texas showing outcrop of Glen Rose Formation. (After R. T. Hill.) 1, location of Glen Rose tracks. 2, location of Hamilton County tracks.

A spot was selected at random, and the soil was removed from a space about four feet square. Three well-defined tracks were exposed within this space, and four others were less clearly recognizable (Fig. 3). At six other spots the soil and gravel were removed

from patches two to four feet square, and in each instance one or more tracks were found. Some of the tracks were shallow, due to the abrasion of gravel swept over the bed rock by the swift water of freshets, and others were rendered indistinct by superimposed tracks. The creek bed, which is floored with the stratum carrying the tracks, varies in width from four to twelve feet for a distance of about 800 feet. On the basis of the writer's observations, he is convinced that the estimate made by residents of the neighborhood, placing the number of tracks at considerably over a hundred, is not likely to be extravagant. This number could quite likely be considerably increased by clearing away the slumped material along the foot of the caving banks. Reliable parties who have seen the locality when the whole expanse of rock in the creek had been swept clear of its covering state that it exhibits a maze of tracks for fully two-thirds of the foregoing distance. Near the lower or southern end of the rock exposure, where erosion has cut through the level-lying stratum bearing the tracks, a marginal expanse of the limestone on either side of the channel shows that the tracks are infrequent or entirely absent, but northward they are known to be present until the rock disappears under the stream bed.

FIG. 2.—Cottonwood Creek along bed of which dinosaur tracks are found. (Photo by C. B. James.)

The footprints examined varied in length from eight to twenty inches. A plaster cast made by Mr. C. B. James, of Hamilton,

shows the dimensions indicated in Figure 5. This particular track was covered with deep mud at the time of the writer's visit, but enough mud and water was baled out to determine that it was only one of three large tracks within a space of scarcely more than a square yard.

Near the southern end of the locality, where the tracks are infrequent, a single, large, well-formed track three or four inches deep and about fifteen inches long was found. Judging the probable direction of movement from the orientation of the track,

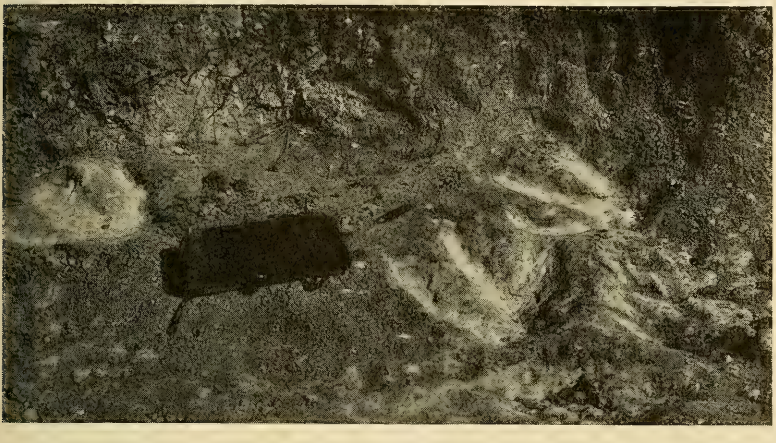


FIG. 3.—Dinosaur tracks in the bed of Cottonwood Creek, Hamilton County, Texas. (The tracks were lightly dusted with white powder to secure definition in the photograph.)

it appeared that other tracks of the same individual should be present on the uncovered rock. Two saucer-shaped depressions were located in the direction of motion, at intervals of about four feet, which were apparently vestiges of footprints, though quite indistinct. The stride of the animal seems therefore to have been about the same as that measured by Shuler at Glen Rose, and the size of the tracks in the two localities corresponds quite closely. This was the only instance in which the stride of a given individual could be measured, though undoubtedly other instances could be found if the rock were adequately cleared of dêbris.

A correlation of the geologic horizons at which the tracks are found in Somervell and Hamilton counties would be particularly

interesting, but at this time such a correlation cannot be made with any degree of accuracy. Shuler placed the Glen Rose tracks in the middle third of the Glen Rose formation which at that locality has an approximate total thickness of 315 feet.[1] In Hamilton County the interstream divides are capped with basal Edwards limestone containing an abundance of chert. The dinosaur tracks are about 200 feet below the lowest chert bed. Immediately beneath the Edwards limestone are the soft, chalky beds of the

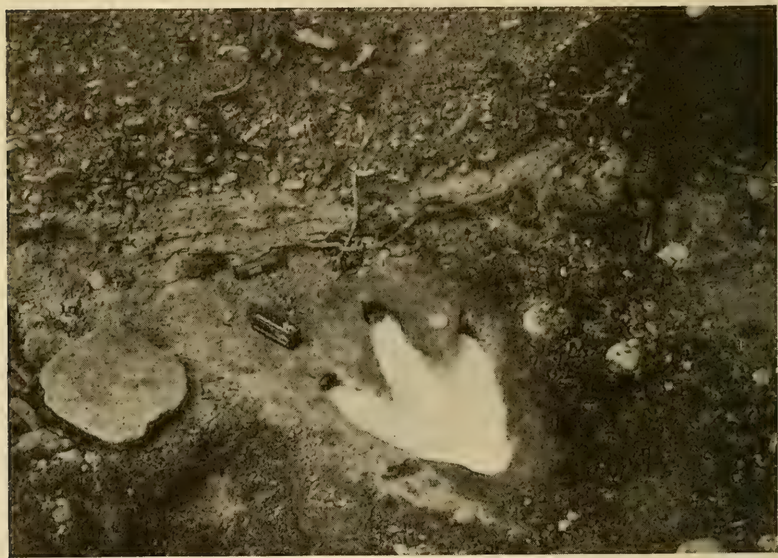


FIG. 4.—Dinosaur track of which dimensions are shown in Figure 5. (Track dusted with white powder.) (Photo by C. B. James.)

Walnut formation, eroded to form a wide, shallow valley, and in the midst of this valley Cottonwood Creek has cut down slightly into the Glen Rose beds. The upper limit of the Glen Rose could not readily be determined in the immediate locality, owing to poor outcrops, but it is tentatively placed about fifty feet above the horizon of the tracks. This tentative correlation is not of much assistance, however, as the total thickness of the Glen Rose is nowhere exposed nearby, and there are no reliable data upon which to postulate thickness in this vicinity. The Glen Rose formation

[1] R. T. Hill, *Twenty-first Annual Report U.S. Geol. Surv.*, Part VII, p. 153.

is probably thicker here than in Somervell County, and northward it thins out and almost completely disappears northwest of Fort Worth, where the Paluxy and Trinity sands, ordinarily separated by the Glen Rose, merge into one thick formation known as Antlers sand.

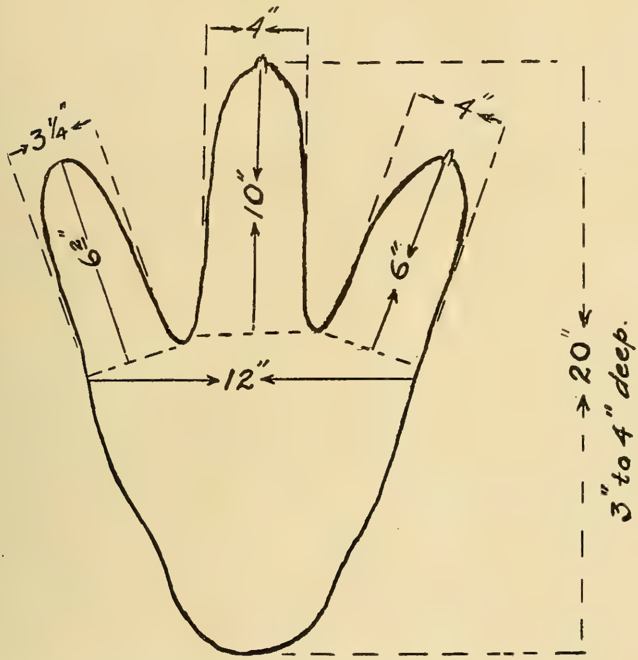


FIG. 5.—Diagram showing dimensions of track in Figure 4

It is interesting to note that R. T. Hill in 1886 found dinosaur bones in the upper strata of the Basement sands of the Lower Cretaceous near Lambert, Parker County,[1] and that he assigned the name "Dinosaur sands" to this horizon.[2] It is reasonably certain that the beds in which the bones were found are approximately the equivalent of those in which the tracks occur in Somervell and Hamilton counties.

The writer expresses no opinion as to whether the tracks in the two localities were made by dinosaurs of the same species. The

[1] *Twenty-first Ann. Rept. U.S. Geol. Surv.*, Part VII, p. 192.

[2] *Amer. Jour. Sci.*, third series, Vol. XXXIII (April, 1887), p. 298.

general shape of the tracks seems to be slightly different. After examining one of the Somervell County tracks, now in the museum of Southern Methodist University at Dallas, it is noticeable that the heel prints shown in Figures 3 and 4 are proportionately longer, narrower, and usually much better developed than in the Glen Rose tracks. The shape of the heel is shown quite clearly in Figure 4. This difference may be due to the fact that the animal, when walking, did not press down heavily on the heel, but carried the weight thrown forward on the toes. The Glen Rose tracks were quite certainly made by an animal in motion, while those in Hamilton County, with the better development of the heel, may have been made in more of a resting position. It would be interesting to make a comparison of a number of the Hamilton County tracks, to see whether this difference is characteristic of all the tracks found there.

Dinosaur tracks, exclusive of those found in the Texas Cretaceous, have usually been preserved in sandstone which clearly indicates littoral deposition. The tracks were evidently made by animals walking along a wet, sandy beach or in very shallow water. Shuler adequately discussed this problem in the paper referred to above, and the writer concurs in the conclusions there set forth. The tracks seem to have been made in a soft or plastic ooze which was probably covered by several feet of water. This "lime mud" was probably deposited in broad, shallow, quiet seas, relatively free from currents. There is no noticeable amount of sand in the immediately associated strata. Blue-clay shales carrying selenite crystals occur for at least fifteen feet above and three or four feet below the limestone, and in the overlying shales are thin lenses of coquina bearing a typical Glen Rose fauna.

Mr. C. B. James, of Hamilton, who called the writer's attention to the locality, sent a brief description of the Hamilton County tracks, accompanied by photographs, to the Smithsonian Institution, and in a reply C. W. Gilmore wrote:

> These are in all probability the footprints of one of the large three-toed dinosaurs. Similar footprints have been reported to the authorities of the Institution from near Glen Rose, Texas. The fossil remains of an animal known as Trachodon, have been found in Cretaceous rocks of Texas, which are of sufficient size to have made such tracks as those depicted.

PROBLEMS IN STRATIGRAPHY ALONG THE ROCKY MOUNTAIN TRENCH

FRANCIS PARKER SHEPARD
University of Chicago

In an investigation of the structure of the Rocky Mountain trench, from Gateway, Montana, to Golden, British Columbia,[1] the writer came in contact with some of the stratigraphic problems of the Canadian Cordillera. For determination of fossils and for helpful criticism he wishes to acknowledge his indebtedness to Dr. Stuart Weller.

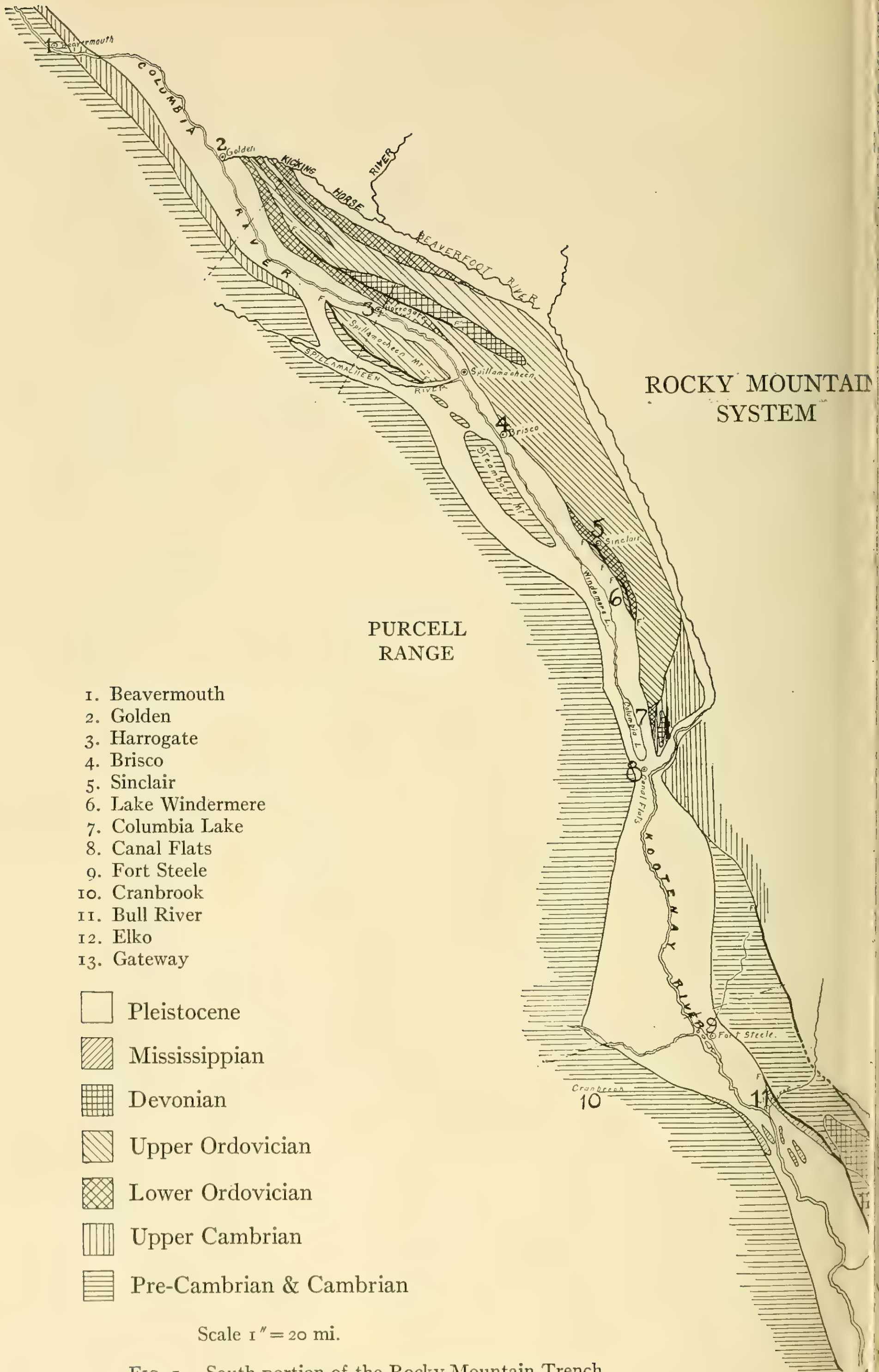
STRATIGRAPHIC SERIES ALONG THE ROCKY MOUNTAIN TRENCH

From the fossils collected at various localities and the sections which have been previously made of the trench, it was possible to map with some degree of accuracy a large part of the zones flanking this great valley (Fig. 1). There are two principal series of rocks represented. One of these is dominantly clastic, the other dominantly limestone. The former contains many metamorphic varieties of shales, sandstones, and conglomerates, but the metamorphism is not extreme. Limestone is not lacking in the clastic series, but most of it is in thin bands. (For convenience this series will be termed the "clastic series.")

The age of these formations is somewhat problematic. In those places where it has been studied hitherto, it has been generally considered pre-Cambrian, but fossils found recently in one locality have shown part of it at least to be as young as Lower Cambrian.[2] That the series is older than Upper Cambrian is indicated by the following points: (1) In a number of places it was found underlying Upper Cambrian formations, and nowhere has it been observed overlying formations containing Paleozoic fossils. (2) It is in general metamorphosed more than formations of the limestone series.

[1] F. P. Shepard, *Jour. Geol.*, Vol. XXX (1922), p. 130.

[2] S. J. Schofield, *Science*, Vol. LIV (1921), p. 666.



Scale 1″ = 20 mi.

Fig. 1.—South portion of the Rocky Mountain Trench

(3) Fossils were found only in one place, while in the other series they were abundant. No attempt has been made to divide or correlate the different members of the clastic series, because of the great difficulty and the extremely detailed work necessary for classification of unfossiliferous formations in a folded region. A part of it is probably pre-Cambrian.

In the limestone series fossils of the following ages have been found: Upper Cambrian, Lower Ordovician, lower Richmond, upper Richmond, Upper Devonian, and Mississippian. Also the Middle Cambrian horizon at Elko might be considered as part of the "limestone series." Other horizons, including portions of the Silurian, are possibly present. Disconformities are common, showing that there was considerable oscillation of the areas of active deposition. Angular unconformities have not been found but may occur.

Stratigraphic sections were made at several localities along the trench and some of the more representative have been combined into a generalized section (Fig. 2). This section consists chiefly of formations found in the vicinity of Sinclair Springs.

Upper Cambrian and Lower Ordovician.—No stratigraphic break has been observed between the Cambrian and Ordovician in the northern portion of the trench visited. Fossils were collected which have been identified by Dr. Walcott as belonging at the top of the Upper Cambrian, and above this is a horizon containing a fauna identified by Dr. Raymond as corresponding to the base of the Ordovician in Europe.[1] Walcott identified the following species:

Dicellomus sp.
Agnostus sp.
Agnostus sp.
Crepicephalus? fragments of cephalon
Ptychaspis cf. striata Whitfield

The species identified by Dr. Raymond included:

Lingulella moosensis
L. allani
Obolus molisonensis
Eorthis desmopleura
E. sp. (ind.)
Cyphaspis brevimarginata
Hemigyraspis mcconnelli
H. carbonensis
Megalaspis shepardi sp. nov.
Dalmanella hamburgensis

[1] P. E. Raymond, *Am. Jour. Sci.*, fifth series, Vol. III, p. 204.

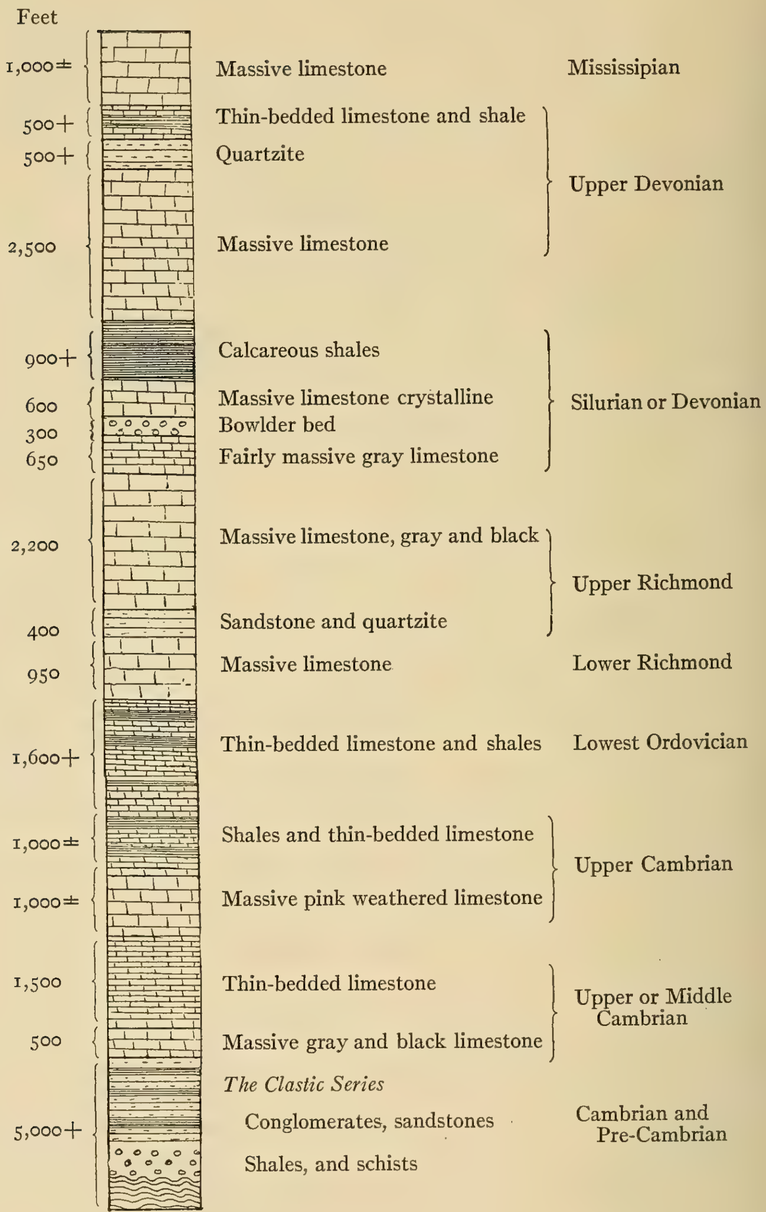


FIG. 2.—Generalized section along the Rocky Mountain trench

Syntrophia nundina
Raphistoma nasoni
Arthrorachis sp. ind.
Hystricurus tuberculatus
Symphysurus cleorus
S. elongatus
Menocephalus sp. ind.

According to Raymond this is a typical Ceratopyge fauna, comparable to that at the base of the Ordovician in Europe. It has been found in several other localities in the west directly overlying the Upper Cambrian, and Dr. Raymond thinks that it implies the absence of the Ozarkian series from the west.

Upper Ordovician and Silurian.—Comparing the section made by Allen[1] along the main line of the Canadian Pacific with that of the trench, there are seen to be some resemblances but several important differences.

SECTION ALONG THE CANADIAN PACIFIC

(After Allen)

System	Formation	Thickness	
		Feet	Meters
Mississippian	Lower Banff shale	1,200	366
	Lower Banff limestone (partly Devonian)	1,500	457
Devonian	Intermediate limestone	1,800	548
	Sawback limestone (Devonian ?) (thickness, 1,128 m.)	....	....
Silurian	Halysites beds	1,850	563
Ordovician	Graptolite shale	1,700	518
	Goodsir shale	6,040	1,841
Upper Cambrian	Ottertail limestone	1,725	526
	Chancellor shales	4,500	1,372
	Sherbrooke limestones	1,375	419
	Paget limestones	360	110
	Bosworth limestones	1,855	565
Middle Cambrian	Eldon limestones	2,728	831
	Stephen limestone-shale	640	196
	Cathedral limestones	1,595	486
Lower Cambrian	Mt. Whyte sandstone shale; St. Piran quartzite; Lake Louise shale and sandstone — Rocky Mountains	....	....

[1] J. A. Allen, *Can. Geol. Surv. Guidebook No. 8,* Part 2, p. 120.

In Allen's section the Halysites limestone is placed in the Silurian. This formation, however, contains the same fauna that is found in the formation considered upper Richmond in the accompanying section (Fig. 2). The fauna contains the corals which are generally typical of the Silurian, namely Halysites catentulatus, Favosites, but these are also known to occur in the west in formations which are generally considered to be Ordovician,[1] as for example in the upper portion of the Big Horn limestone. The fauna also includes characteristic Upper Ordovician (Richmond) brachipods among which a form of Rhynchotrema capax is most common. Whether Silurian strata are actually present in the section is open to question. In two localities, overlying the upper Richmond and underlying formations of Devonian age, there are several thousand feet of limestone and shale in which no fossils were found. In one locality the upper Richmond is overlain by a bowlder bed which strongly suggests tillite,[2] and as Silurian tillites have been reported in southeastern Alaska[3] at a similar horizon, it is possible that this formation is of the same age.

Devonian.—The Devonian seas probably invaded the Rocky Mountain trench from two directions. An invasion from the south by an arm of the Jefferson seas, which covered most of the Rocky Mountain region of the United States, is believed to have occupied the southern portion of the trench. Formations of this age have been found by Daly at the international boundary line[4] and again farther north near Elko and Canal Flats by Schofield.[5] The fossil species collected from this formation, which are also known to be present in the Jefferson limestone are Spirifer englemani and S. utahensis, both of which are guide fossils for the Jefferson.

Highly fossiliferous Devonian strata were also observed a mile east of Harrogate in the Beaverfoot Range. The fauna is unlike that of the Jefferson limestone, but is related to that of the Devonian formations off the MacKenzie River district to the north,

[1] N. H. Darton, *Bull. Geol. Soc. of Am.*, Vol. XV, p. 399.

[2] F. P. Shepard, *Jour. Geol.*, Vol. XXX (1922), p. 89.

[3] E. Kirk, *Am. Jour. Sci.*, fourth sec. (September, 1918), p. 511.

[4] R. A. Daly, *Geol. Surv. Can. Mem. 38*, p. 115.

[5] S. J. Schofield, *Geol. Surv. Can. Mem. 76*, p. 53.

an occurrence which suggests the extension of an arm of the MacKenzie Devonian sea into the northern part of the trench. The fossil forms in this fauna which are also known in the MacKenzie Devonian include the following species:

Martinia meristoides	Spirifer tulia
Reticularia fimbriata	Atrypa reticularis
Schizophoria macfarlini	Astraespongia hamiltonensis
S. striatula	Heliophyllum halli

a faunal group which suggests late Middle or early Upper Devonian age.

Whether this invasion from the MacKenzie basin was contemporaneous with that from the south, with the two submergences separated by a land barrier in the Lake Windermere district, is not established, but the invasion from the north was probably somewhat later than that from the south.

Mississippian.—The Mississippian is known to occur only in the southern portion of the trench in the vicinity of Wardner and Bull River, where it was discovered by Schofield.[1] Dr. Raymond identified the following species:

Camarophoria explanata	Cleiothyridna crassicardonalis
Camaroechia cf. C. metallica	Spirifer cf. S. centronatus
Composita madisonensis	Productella cooperensis

RELATION OF PRE-CAMBRIAN TO CAMBRIAN

The stratigraphic relation of the Cambrian sediments to the pre-Cambrian formations in the Canadian Cordillera has been the subject of considerable discussion. Daly considers the two series to be essentially conformable, while Walcott and Schofield think them unconformable.

The situation along the main line of the Canadian Pacific is well summed up by Daly in his report of the "Reconnaissance between Kamloops and Golden."[2] The thick lower Cambrian fossil-bearing members have at their base a conglomerate (the Fairview formation). Below this the Hector Shale is considered

[1] S. J. Schofield, *Geol. Surv. Can. Mem. 76,* p. 57.

[2] R. A. Daly, *Geol. Surv. Can. Mem. 68,* pp. 87–93.

to be pre-Cambrian. Walcott[1] believes that between these two formations there is an unconformity, shown by the following: (1) The overlying conglomerates contain fragments of the Hector shale. (2) Slight hollows in the Hector shale are filled with thin sandstone lenses. (3) The underlying Beltian (Proterozoic) formation varies in character at the contact from place to place. (4) The sediments seem to change from brackish water in the Beltian, to marine in the Cambrian. (5) Allen's discoveries of the contact between the Hector shale and the Fairview formation showed apparent conformity in one place, while in two others discordance of dip of 4°.

Daly makes the following reply to these arguments: (1) The fragments of the Hector shale in the overlying Fairview conglomerate are all angular and do not show a significant time break. (2) The Fairview is nearly identical with formations occurring at various horizons in the pre-Cambrian. (3) The sandstone beds in the upper surface of the Hector are merely lenses which are common elsewhere in the Beltian. (4) The discordance of dip seen between the Hector and the Fairview can be explained by irregularities in uplift as such are seen in continuous sedimentary series in many localities. (5) The Selkirk series is divided on lithological grounds into Cambrian and pre-Cambrian with the dividing plane in the Ross quartzite, where there is no sign of unconformity.

Daly's first four points appear to be sound. Walcott's arguments for an unconformity lack proof that a time break is represented. There might well have been a change in the conditions of sedimentation without unconformity. In the natural order of clastic sedimentation it is to be expected that there will be some stirring of older sediments by changes in the activity of the currents. In the "clastic series" along the west side of the trench many examples of such disturbances are found. It seems that more evidence is necessary here to warrant the conclusion of an unconformity of importance between the two systems. Minor disconformities are of course present in great numbers in most thick sedimentary series, especially if there are clastic sediments.

[1] C. D. Walcott, *Smithsonian Misc. Coll.*, Vol. LVII, p. 343.

In regard to Daly's fifth point concerning the Selkirk series, recent evidence shows that the age of the series is very uncertain.[1] As stated above, Daly places the dividing line between the Cambrian and the pre-Cambrian in the Ross quartzite, because of lithological resemblances of the sequence of formations in the Canadian Rockies and the Selkirks, but the discovery of upper Paleozoic fossils in the Laurie formation, which underlies the Ross quartzite formation by 12,650 feet and is separated from it by the Nakimu limestone and the Cougar quartzite, disproves this conclusion.

A recent observation further complicates the situation.[2] The Cougar quartzite was found underlying the Upper Cambrian

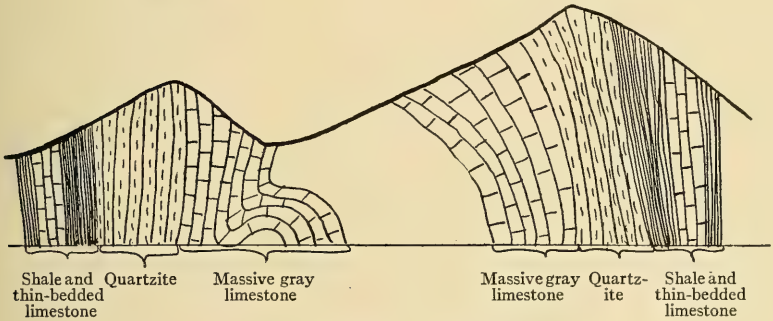


FIG. 3.—Section at Harrogate

shales and limestones on the west side of the trench at Golden, and, while a detailed study of the contact was not made, it appears probable that there was at least no angular unconformity separating the two formations. Therefore one discovery places the Cougar formation above upper Paleozoic fossils and the other places it below the Upper Cambrian. It seems probable that the series in the Purcell Range is not of the same age as that in the Selkirks, a conclusion which seems more likely when it is considered that the section in the Purcell Range exhibits only a part of two of the formations which are present also in the Selkirks (Fig. 3).

[1] L. D. Burling, *Bull. Geol. Soc. Am.*, Vol. XXIX, p. 146.

[2] F. P. Shepard, *Jour. Geol.*, Vol. XXX (1922), p. 146.

In the southern part of the trench Daly and Schofield are not in agreement as to the dividing line between the Cambrian and the pre-Cambrian. In Daly's "Forty-ninth Parallel Survey" the division between the Cambrian and the Beltian was placed within the "clastic series" between the Altyn formation below and the Hefty formation above.[1] This report was based on reconnaissance work in the field, and the division of the unfossiliferous formations was necessarily quite arbitrary. Schofield's more detailed work in the Cranbrook area[2] made changes in Daly's classification and produced more evidence concerning the age of the unfossiliferous series. He found Middle Cambrian fossils in the Burton formation near Elko, and below this, while there are no angular unconformities, there are marked signs of disconformity. There is a thin basal conglomerate at the base of the Middle Cambrian, and the surface of the Roosville formation beneath is somewhat weathered. From these facts Schofield concluded that there is an unconformity at the top of the Lower Cambrian, and placed the Roosville in the pre-Cambrian. Since the Roosville is the highest member of the "clastic series" (which is represented), this places all of that series in the pre-Cambrian. Recently, however, Colonel Pollin discovered a remarkably fine trilobite fauna in a formation which is probably lower than the Roosville. According to Walcott the fossils indicate a horizon at the top of the Lower Cambrian. Therefore the extent of the disconformity near Elko is minimized, and incidently Daly's original dividing line between the Cambrian and the Beltian is more nearly correct than that of Schofield.

However, Schofield has again attempted to find an unconformable relation between the Cambrian and the pre-Cambrian.[3] His evidence for this includes: (1) The thickness of sediments of the Siyeh formation between the Purcell lava and the basal conglomerate of the Lower Cambrian, varies from a few feet to 300 feet. (2) The lithological and metamorphic contrast above and

[1] R. A. Daly, *Geol. Surv. Can. Mem. 38,* p. 179.

[2] S. J. Schofield, *Geol. Surv. Can. Mem. 76,* pp. 41–52.

[3] S. J. Schofield, *Science,* Vol. LIV, p. 666.

below is marked. (3) Basal conglomerates of the Cambrian have rounded fragments of the underlying argillites.

This evidence does not necessarily place the underlying Siyeh formation in the pre-Cambrian. That the Olenellus horizon is not nearly at the base of the Cambrian is shown by the great thickness of Lower Cambrian below the Olenellus horizon in the Waucobian of California. Whether the length of the time bridged in this disconformity is sufficient to place the underlying formations in the Beltian, is open to doubt for the following reasons: (1) The degree of metamorphism varies greatly in members of the same age in the Purcell series. (2) The difference in the thickness of the Siyeh formation is not important, because of its clastic nature. (3) The occurrence of the conglomerate does not prove an unconformity, as conglomerates are common in the "clastic series." (4) Since there are great abundance and all varieties of argillites in the "clastic series" the fragments of argillites in the Cambrian conglomerates may have come from argillites other than those directly underlying the conglomerate. In general it may be said that minor unconformities are to be expected in a series of this sort, and their significance is not great. Since the contact of the Cambrian on the pre-Cambrian has been especially well studied, it is not surprising that minor unconformities should be found at some horizon not far below the lowest horizon that is known to be fossiliferous.

From observations on the relation of the "clastic series" to the "limestone series" farther north in the trench, new but rather incomplete evidence was found of the relation between the older series and the Upper Cambrian limestones (the base of these limestones may be Middle Cambrian). At Premier Lake, below what are probably the Upper Cambrian limestones, there is a series of argillaceous quartzites and shales. While no accurate measurement of the series was made, it was estimaetd to be at least 5,000 feet thick. As the series was examined in several places and was found to be quite similar in character in all of them, the condition of sedimentation is thought not to have varied in any important degree. This series is probably, at least in part, of the same age as the Purcell and Galton series farther south. The Purcell series

is only 15 miles to the south in the Fort Steele region, and appears to be traceable this far north. The clastic nature of the deposits as against the limey deposits of the Upper Cambrian (and perhaps Middle Cambrian) indicates that there was variation in the character of the sedimentation in the Cambrian. In the vicinity of Parsons the Upper Cambrian is somewhat argillaceous, but the base of the Ordivician is mostly limestone.

If the Beltian is actually present at the base of the "clastic series," it seems as though the greatest change during the Beltian and Cambrian times was a change from semiterrestrial and near shore deposits to deposits in clear broad seas. Probably this change is of more importance than any minor unconformities that may exist below the lowest rocks which are known to contain fossils.

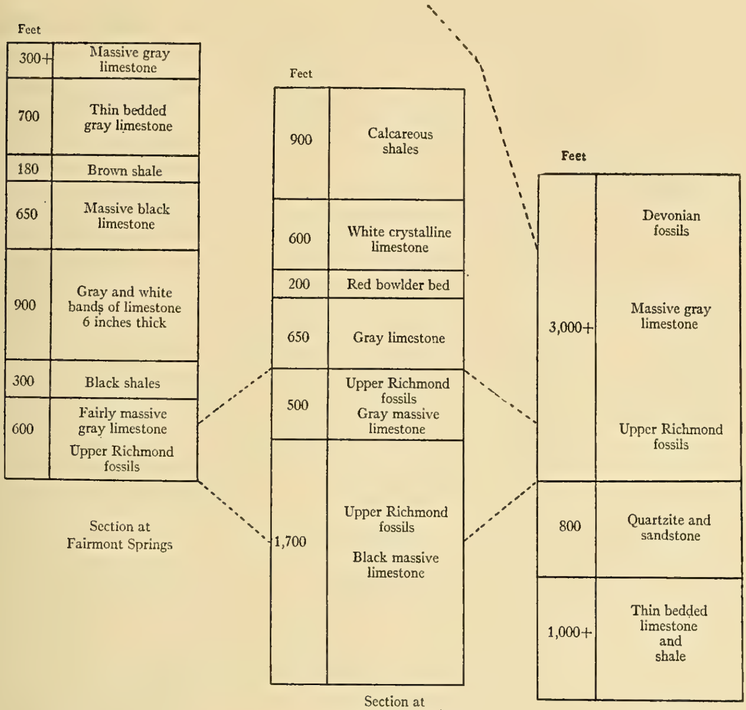
CORRELATION OF UNFOSSILIFEROUS FORMATIONS

Correlation of the unfossiliferous formations over wide areas by lithological comparison has been resorted to frequently in the Cordillera. Dawson, McConnell, and others who made the pioneer surveys of the region relied especially on this method. Daly, as has been shown above, also correlated formations of widely separated portions on the same basis. Mistakes made in one of these attempts is illustrated by the recent findings concerning the Purcell series (p. 369).

The most detailed work on the unfossiliferous formations is that by Schofield in the Cranbrook area. Here the members of the Purcell series are mapped over an area of about 2,500 square miles. The characteristics of the different formations are such that they are likely to vary considerably, and to grade from one into another rather readily, so that with the great complication of the fault system in the region, a classification is extremely difficult.

From observations based chiefly on the fossiliferous formations, it appears that classification of the unfossiliferous formations is especially complicated by the extreme variability of the lithology, and of the metamorphic character of the formations along the trench.

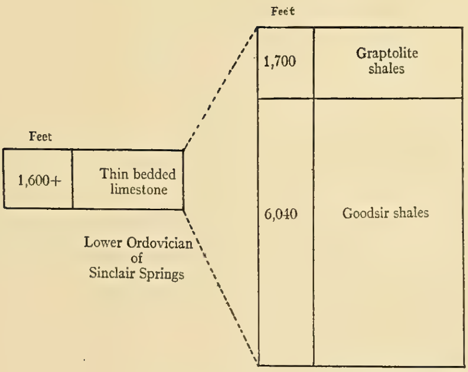
Lithological variations.—The lithological character of the different horizons in the Paleozoic was examined at several places along



Section at Fairmont Springs

Section at Sinclair Springs

Section at Harrogate

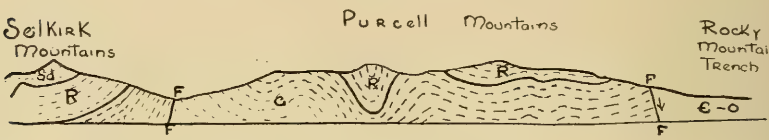


Lower Ordovician of Sinclair Springs

Lower Ordovician East of Golden (after Allen)

the east side of the trench. The change in the character of the beds containing the same faunal succession was the more notable because the formations were dominantly calcareous. A few sample sections (p. 373) will illustrate this point.

The lithology of a section east of Harrogate (Fig. 4) would indicate that there is an anticline or syncline forming the summit of the Beaverfoot Range, because of the apparent repetition of



Є-O = Ordovician and Upper Cambrian
Sd = Sir Donald quartzite (Lower Cambrian)
R = Ross quartzite (Lower Cambrian and Beltian)
C = Cougar quartzite (Beltian)

Section along the main line of the Canadian Pacific Railway (after Daly)

Є-O = Ordovician and Upper Cambrian
R = Ross Quartzite (Upper Cambrian ?)
C = Cougar Quartzite (Cambrian ?)

Same section revised

FIG. 4

the same formations in reverse order on the two sides. However, fossils proved that this reversed succession was a mere coincidence, and, as shown in the section, one side of the supposed anticline is Devonian and the other Ordovician. An occurrence of something of this sort in the Cranbrook area, or wherever else fossils were lacking, could very easily introduce error into the classification.

Metamorphic variations.—Metamorphic variations are especially important in the Purcell Range on the west side of the trench. This is perhaps especially true in the Cranbrook area, where there are more igneous intrusions than farther north, but

even where the intrusions are absent metamorphism is found to vary greatly. In the Selkirk Range along the main line of the Canadian Pacific Railway, where there are no intrusives, the upper Paleozoic Laurie formation contains the same type of semi-metamorphic beds as are found farther east in the lower portions of the Cambrian. Many of the upper Paleozoic rocks of the Arrow Lake region are more metamorphosed than the pre-Cambrian (or early Cambrian) beds to the east in the Cranbrook area. This last case is probably explained by contact metamorphism.

A quartz grit having well-rounded quartz pebbles and a calcareous cement was found in several places along the west side of the trench in the vicinity of Lake Windermere. This formation was associated with argillaceous rocks which varied from shales to schists in the different localities, although it most likely represents the same horizon because of its very distinctive characteristics, which were not found in any other formation.

At Sinclair Springs there is a bed of highly crystalline limestone which is higher in the stratigraphic series than another limestone which is not crystalline. So many similar cases were found that it seems as though the anamorphic influences along the trench were very irregular. The cause of this irregularity is varied. In the southern Purcells, the intrusions are chiefly responsible. Farther north the intrusives rarely appear at the surface, but their presence below the surface is shown by the hydrothermal alteration of the rocks in many places along the west side of the trench. In the northern portion, however, the most important anamorphic results are connected with diastrophic movements. In the vicinity of large faults the alteration is often more pronounced than elsewhere. The Purcell Range was probably deformed at two periods[1] so that the formations on that side would tend to be differently metamorphosed from those of corresponding age on the other side. At present the exposed pre-Cambrian and later formations are found at the same general level, but formerly the pre-Cambrian was more deeply buried. As deformation went on, the pre-Cambrian was brought gradually toward the level of the younger formations by folding and faulting. After the two reached

[1] S. J. Schofield, *Geol. Surv. Can. Mem. 76*, p. 101.

the same level, metamorphism would tend to be somewhat equal in effects on each. Before that time the more deeply buried pre-Cambrian would tend to be more severely metamorphosed unless it was below the zone in which the most effective compression was being concentrated. Further confusion in regard to differential metamorphism may be produced by the cutting of great valleys in the rising mountain ranges. Along the lines of these valleys the overburden is less, and therefore there would be less severe metamorphism. Thus the amount of metamorphism of a local series of rocks in this general region can only be used to tell its relative age in exceptional cases.

The foregoing consideration of the varying character of the lithology and metamorphism is intended to show how extremely difficult it is to correlate unfossiliferous formations in a mountainous region. Attempts at such correlations are of course suggestive, but they should be duly qualified.

A SCALE OF GRADE AND CLASS TERMS FOR CLASTIC SEDIMENTS[1]

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CONTENTS

INTRODUCTION

In no other science does the problem of terminology present so many difficulties as in geology. With the growth of knowledge in any field of investigation, men devise new terms or redefine old ones in the attempt to convey more precise and definite ideas. In all the branches of science much confusion has followed the redefinition of old terms because of the indiscriminate use of the terms both in the old and the new senses. But in geology, difficulties of this kind are peculiarly great.

Because geology is a field science and has followed in the footsteps of exploration, it has acquired terms from all parts of the world. Many of the names for the less common special features have come from the dialect or colloquial speech of that part of the world where they are best developed. With the use of these terms of geologists of other regions, much irregularity of usage and hence much confusion has arisen.

Since 1917, the writer had been engaged in the study of abrasion and shaping of cobbles and pebbles by the action of running water. In the course of this study the loose usage of cobble, pebble, and related terms (in which his own practice was no exception) has impressed him with the need of greater uniformity of usage and

[1] Published by permission of the Director of the United States Geological Survey.

more careful definition of such terms. With this need in mind, he sent to about sixty of his colleagues of the United States Geological Survey a questionnaire asking them to give the limiting dimensions in their conception or usage of the terms bowlder, cobble, pebble, sand grain, and clay particle. Replies were received from about thirty of the men. These were studied and compared and the composite results presented in preliminary unpublished form which was distributed to more than one hundred geologists throughout the country in the hope of receiving additional comment and criticism. A small number of very helpful replies were received and utilized in modifying, to some extent, the size limits and the terms used.

Early in 1921, mimeographed copies of this modified scheme of terms were sent to about a dozen geologists in this country and England who were known as workers in the field of sediments and sedimentary rocks, and deemed competent to criticize the usages proposed. They were asked to reply to specific questions in regard to the terms which had been subject to the most criticism and to comment in general upon the plan. The replies from this smaller group were most gratifying, since nearly every geologist addressed sent a reply which the writer found useful in the preparation of the classification here presented.

In addition to the studies mentioned above, the writer commenced in 1920 the collection of definitions of sedimentary rock terms. These definitions are taken verbatim from textbooks, dictionaries, encyclopedias, and glossaries. They are typewritten on cards with the proper references and filed under the name of the term defined. Many of the definitions collected are from sources seventy-five to one hundred years old and represent the former usage of certain terms as understood by the compiler. The definitions collected in this way vary greatly in value and none is to be regarded as of absolute authority. They constitute, however, part of the data of the problem.

As will appear from the foregoing, the writer has compiled the present scheme of classification in part from a specific study of the terms here presented and in part from the results of a general consideration of terms in the field of sedimentary rocks. He is

indebted to a large number of geologists who have helped him by spoken and written criticism. Space will permit acknowledgment of gratitude only to Dr. M. I. Goldman and to Dr. J. B. Woodworth, whose interest and frank criticism have been especially helpful in the preparation of this paper.

THE GRADE TERMS

It is the writer's purpose here to suggest terms which are specific as regards size of piece and, at least for the larger pieces, as regards shape of piece. The terms of this scheme apply to rounded materials in so far as materials of the size in question become rounded by transportation. Strict uniformity in this regard will not fit the sediments as they occur in nature. Bowlders, cobbles, and pebbles are rounded rock fragments, whereas most clay particles are angular, yet geologists will recognize that they all belong to a natural series. Likewise, bowlders and clay particles are not commonly of the same mineral composition but in spite of this fact they are the two extremes of the series of transported rock fragments. By an excessive multiplication of terms it would be possible to make a classification in which each term was specific as to size of particle, shape of particle, lithologic character, and other characteristics. Such a scheme would be highly artificial in many of its categories and seems to the writer impracticable in the present state of knowledge.

The present scheme of grade terms is, accordingly, just what its name implies—a series of names for clastic fragments of different sizes. They apply only to rounded fragments except in the case of fine sands, silts, and clays in which even prolonged transportation does not always round the pieces. The names applied to the different grades carry no lithologic, mineralogic, or chemical significance so far as the present scheme is concerned. Sands are dominantly quartzose, whereas clays are largely made up of kaolin, but this fact is incidental and not necessary in the use of the terms.

FRAGMENT TERMS

Bowlder.—This term is in common use in English-speaking countries for rounded and smoothed masses of rock larger than

cobbles[1] resulting from abrasion in transportation. Angular masses of rock of the same size are commonly called blocks or slabs. The word bowlder is related to the English word *bellow*; compare Swedish *bullra*, to *rattle* or *roar*. Equivalent terms in several other languages carry similar ideas of rumbling or rolling in their derivation.

Cobble.—Cobble or cobblestone is used generally, both by geologists, and in common speech, for a rounded stone smaller than a bowlder and larger than a pebble. The term is a diminutive of the word *cob*, meaning a rounded hump or knob, and related to the German *Kopf*, for head.

Pebble.—This term is a very ancient one which is used commonly for rounded, transported rock fragments smaller than cobbles. In the past it was more commonly used than it is at present for rounded stones up to the size of bowlders. The tendency now is to use the term cobble in an intermediate sense, as stated above. Pebble is from the Anglo-Saxon *papol*, which meant something small and round, perhaps akin to the Latin *papula*, a *pustule*.

Granule.[2]—The term granule is here proposed by the writer as a term for rounded rock fragments larger than very coarse sand grains but smaller than pebbles. Rounded pieces too small to be called pebbles have still been too large to be called sand grains in the practice of most geologists. Granule is from the Latin *granulum*, diminutive of granum, *grain*, meaning a *little grain*, a *pellet*. In spite of apparent infelicity of meaning (little grain), this term was chosen as best adapted for this grade of material. The term grit grain was considered for use in this sense, but was thought less satisfactory. Grit is used in another sense, as for fine sandstone of angular grain. It seemed undesirable to include these grains either with small pebbles or with coarse sand grains, and it is hoped that the term granule may fill an apparent gap in the series of terms heretofore used.

Sand grain.—The several terms made up by the use of adjectives qualifying sand grain are self-explanatory.

[1] For explanation of the basis on which the sizes limiting the several grades were chosen, see the text which follows.

[2] This term was suggested to the writer by Dr. Herbert A. Baker, of England.

Silt particle.—The term silt particle is here applied to individual particles smaller than very fine sand grains but larger than clay particles. The term silt from which it was derived was objected to by some geologists on grounds that are stated under the heading of silt. These grounds were not sustained even by a minor part of the data available to the writer and the term is here used as the most satisfactory one.

TABLE I

THE GRADE TERMS

The Pieces	The Aggregate	The Indurated Rock
Bowlder	Bowlder gravel	Bowlder conglomerate
256 mm.		
Cobble	Cobble gravel	Cobble conglomerate
64 mm.		
Pebble	Pebble gravel	Pebble conglomerate
4 mm.		
Granule	Granule gravel	Granule conglomerate
2 mm.		
Very coarse sand grain	Very coarse sand	Very coarse sandstone
1 mm.		
Coarse sand grain	Coarse sand	Coarse sandstone
1/2 mm.		
Medium sand grain	Medium sand	Medium sandstone
1/4 mm.		
Fine sand grain	Fine sand	Fine sandstone
1/8 mm.		
Very fine sand grain	Very fine sand	Very fine sandstone
1/16 mm.		
Silt particle	Silt	Siltstone
1/256 mm.		
Clay particle	Clay	Claystone

Clay particle.—After consideration of several other terms for the materials finer than silt, the term clay was finally adopted as most likely to meet with general approval. Clay particle is therefore used for the individual pieces.

The size limits.—In fixing the limiting sizes of the several grades of the scheme shown in the table, the writer has been governed by two considerations. First, there is a growing acceptance among geologists and engineers of a series of sieves for the classification of natural clastic materials in which the openings of consecutive size stand to one another in the ratio 2 or $\sqrt{2}$ starting with 1 mm. as the standard.

It has long been recognized that the differences between two consecutive screen size openings should be greater for the large sizes than for the small. This principle is followed in the selection of such limits as 1, 2, 5, 10, 20 millimeters, making the limits fall on convenient whole numbers in the decimal notation. This series, however, is a crude approach to a geometrical series in which each value bears a constant ratio to the preceding one. A geometrical series is the ideal for such a purpose, since a change of 1″ is of the same significance and importance in the size of 10″ cobbles as a change of $\frac{1}{10}$″ in the size of 1″ pebbles. Only by the use of logarithmic or some similar graphical scheme of representation can the size composition data be shown adequately for great size ranges. The use of a geometrical series makes the successive grades fall into equal units on the graph—an arrangement much easier to read and interpret than any other known to the writer. The most convenient ratio for the construction of such a series is the ratio 2, and the most convenient and logical starting-point, 1 mm. A large number of mechanical analyses of sediments made with screens and by microscopic measurement conforming to such a series have been made.[1] If a more minute subdivision is needed, the ratio $\sqrt{2}$ can be used, giving twice the number of grades, or in exceptional cases $\sqrt[4]{2}$. These extra subdivisions fit in with and form further subdivisions of the fundamental series of the powers of 2. Conformity to this geometrical series is the first consideration which has guided the writer in fixing the limits between the several grade terms.

The second consideration has been the desire to make each of the limits as close as possible to the common practice of the majority of geologists. Figure 1 shows the composite opinions of twenty-eight geologists of the United States Geological Survey, as reported by them in response to a questionnaire on the sizes limiting several of the terms. The table below shows a number of different schemes of classification which have been published. There is a close agreement between some of those shown, but, with the exception of that of Udden, all lack, in the sizes of successive grades, the uniformity

[1] J. A. Udden, "Mechanical Composition of Clastic Sediments," *Bull. Geol. Soc. Amer.*, Vol. XXV (1914), pp. 655–744.

of ratio of the geometrical series which seems to the writer to be essential to any thorough quantitative study of the mechanical composition of sediments.

Using the data shown in Figure 1 and Table II, the writer has selected the limits conforming to the power series of 2 which most closely conform also to the concensus of the opinions

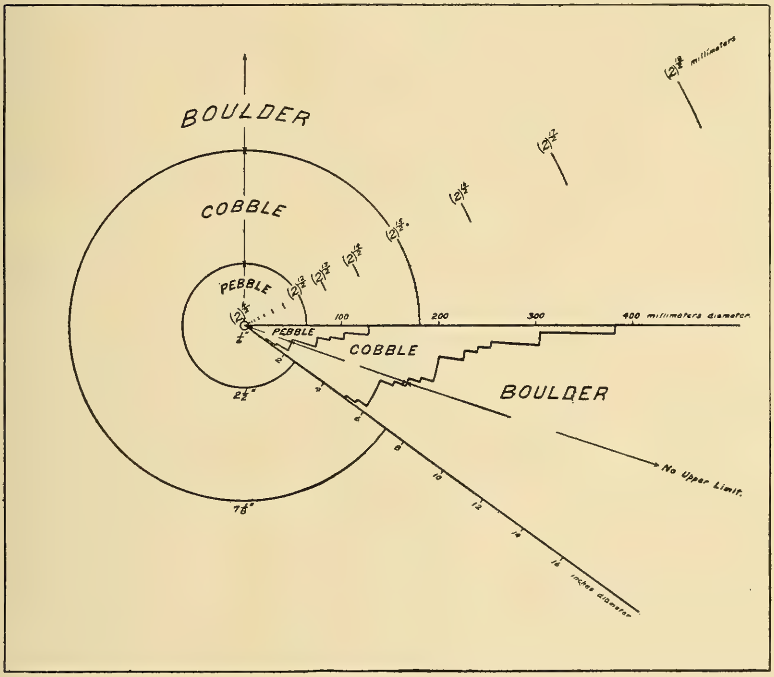


Fig. 1

of authorities quoted there. The names of the several grades thus established were then chosen as described above.

AGGREGATE TERMS

The assignment of definite limiting size values to the terms for the aggregates as named below, as well as the rocks named in another part of this paper, will be objected to on the ground that aggregates are not made up in nature of one grade or even of a few grades, and that therefore the names are inapplicable. The author

TABLE II

New York City* Aqueduct Commission	K. Keilhack†	J. Thoulet‡	A. W. Grabau§	Orth‖	J. S. Diller¶	United States** Bureau of Soils	H. A. Baker††	J. A. Udden‡‡	Classification Here Proposed
Coarse Gravel	Gravel	Fine gravel	Bowlders	Gravel	Gravel	2 mm.	Gravel	256 mm.	Bowlder gravel
5 mm.	2 mm.	3 mm.	150 mm.	3 mm.	2 mm.	Fine Gravel	2 mm.	Large bowlders	256 mm.
Fine gravel	Very coarse sand	Coarse sand	Cobbles	Very coarse sand	Fine gravel	1 mm.	Very coarse sand	128 mm.	Cobble gravel
1 mm.	1 mm.	.89 mm.	50 mm.	1 mm.	1 mm.	Coarse sand	1 mm.	Medium bowlders	64 mm.
Coarse sand	Coarse sand	Medium sand	Very course gravel	Coarse sand	Coarse sand	.5 mm.	Coarse sand	64 mm.	Pebble gravel
.5 mm.	.5 mm.	.45 mm.	25 mm.	.5 mm.	.5 mm.	Medium sand	.5 mm.	Small bowlders	4 mm.
Medium sand	Medium sand	Fine sand	Coarse gravel	Medium sand	Medium sand	.25 mm.	Medium sand	32 mm.	Granule gravel
.25 mm.	.2 mm.	.26 mm.	5 mm.	.25 mm.	.25 mm.	Fine sand	.25 mm.	Very small bowlders	2 mm.
Fine sand	Fine sand	Very fine sand	Fine gravel	Fine sand	Fine sand	.1 mm.	Fine sand	16 mm.	Very coarse sand
.1 mm.	.1 mm.	.04 mm.	2.5 mm.	.05 mm.	.1 mm.	Very fine sand	.1 mm.	Very coarse gravel	1 mm.
Superfine sand	Superfine sand	Fine-fine sand	Very coarse sand	Dust	Very fine sand	.05 mm.	Coarse silt	8 mm.	Coarse sand
.05 mm.	.05 mm.		1 mm.	.01 mm.	.05 mm.	Silt	.05 mm.	Coarse gravel	1/2 mm.
Rock flour	Dust		Coarse sand	Finest dust	Silt	.005 mm.	Silt	4 mm.	Medium sand
.01 mm.	.01 mm.		.5 mm.		.01 mm.	Clay	.01 mm.	Medium gravel	1/4 mm.
Superfine rock flour	Finest dust		Medium sand		Finest silt		Clay	2 mm.	Fine sand
.005 mm.			.25 mm.		.005 mm.			Fine gravel	1/8 mm.
Clay size			Fine sand		Clay			1 mm.	Very fine sand
			.1 mm.					Coarse sand	1/16 mm.
			Superfine sand					1/2 mm.	Silt
			.05 mm.					Medium sand	1/256 mm.
			Rock flour					1/4 mm.	Clay
			.01 mm.					Fine sand	
			Superfine rock flour					1/8 mm.	
			.005 mm.					Very fine sand	
			Clay size					1/16 mm.	
								Coarse silt	
								1/32 mm.	
								Medium silt	
								1/64 mm.	
								Fine silt	
								1/128 mm.	
								Very fine silt	
								1/256 mm.	
								Coarse clay	
								1/512 mm.	
								Medium clay	
								1/1024 mm.	
								Fine clay	
								1/2048 mm.	

* Quoted by A. W. Grabau, *Principles of Stratigraphy* (1913), p. 286.
† Konrad Keilhack, *Lehrbuch der praktischen Geologie* (1908), 2te Auflage, Stuttgart, Ferdinand Enke.
‡ J. Thoulet, *Précis d'analyse de fonds sous-marins actuel et anciens*, p. 64, Paris, R. Chapelot & Cie.
§ A. W. Grabau, *Principles of Stratigraphy* (1913), New York, A. G. Seiler & Company.
‖ Orth, *Bezeichnung des Sandes nach der Grösse des Kornes. Neues Jahrbuch für Mineralogie*, p. 551, Volume for 1875.
¶ J. S. Diller, *U.S. Geol. Surv., Bull. 150* (1902), p. 380.
** United States Bureau of Soils, *Soil Survey Field Book* (1906), pp. 17, 18.
†† H. A. Baker, *On the Investigation of the Mechanical Constitution of Loose Arenaceous Sediments by the Method of Elutriation, with Special Reference to the Thanet Beds of the Southern Side of the London Basin*, p. 2, London, Dulan & Co., 1920.
‡‡ J. A. Udden, "Mechanical Composition of Clastic Sediments," *Bull. Geol. Soc. Amer.*, Vol. XXV (1914), pp. 655–744.

recognizes this difficulty and the grade terms here defined are applicable strictly and without modification to but few natural sediments. They are proposed as the foundation of, and in the course of development of, the several class terms and adjectives proposed in the last part of this paper. Photographs of grade aggregates from 64 mm. to $\frac{1}{32}$ mm. are shown in the accompanying Figures 2 and 3.

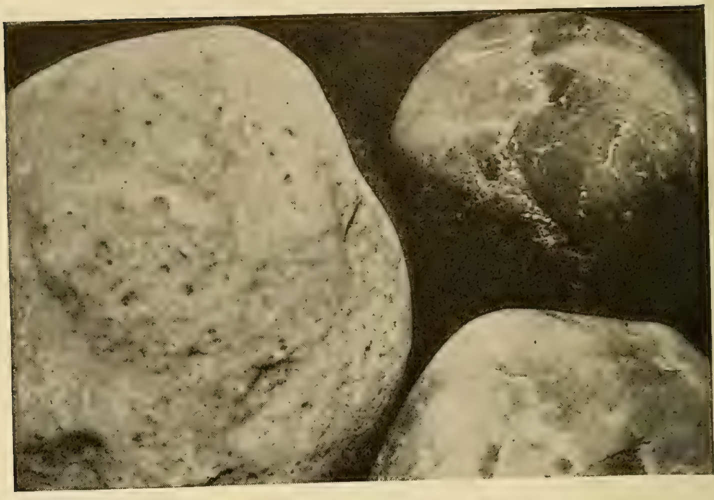
Gravel.—Among some geologists the term gravel has been used only for material composed of small pebbles and granules, but more commonly and especially in America and in reference to glacial gravels, the term has been used to include material containing great bowlders up to a meter or more in diameter, and has recently been so defined by J. S. Flett[1] who considers the term to be the equivalent of conglomerate as applied to the consolidated rocks. It is in this latter and prevailing sense that the term is here used and combined with qualifying words in the terms bowlder gravel, cobble gravel, pebble gravel, and granule gravel.

Sand.—The term sand is in common use among all English-speaking geologists for mineral grains smaller than 1 or 2 mm. and larger than silt. By some writers, sand is applied only to rounded mineral grains, but others use the term more generally. Sand is from the Anglo-Saxon word of the same spelling and meaning.

Silt.—The term silt is considered by some geologists to apply properly to deposits containing organic matter in addition to the mineral particles. The writer was unable to find any considerable support of this view by either past or present authorities, and has here used the term for the grades designated in the table on page 384. The word silt is probably akin to a number of Germanic roots meaning to sift or filter, compare German *seihen, to strain.*

Clay.—After consideration of a number of alternative terms, the term clay has been selected as most likely to be acceptable to geologists for the finest clastic sediments. A few geologists objected to the term on the ground that it implied plasticity or that it referred to a definite chemical composition. It is the view

[1] J. S. Flett, *Encyclopaedia Britannica,* 11th ed. (1911), Vol. XII, p. 382, and Vol. VI, p. 913.



64–32 mm

32–16 mm

16–8 mm

Pebble gravel
Natural Size

FIG. 2

of the writer and of many other geologists that nearly all clastic materials of this grade consist largely of the hydrous aluminum silicates which make up the clay of the chemist and also that the material is always more or less plastic. There is, therefore, in his opinion a common ground for the geologist and chemist without an insistence on the use of the term clay for the pure chemical compounds kaolin or other minerals of this group.

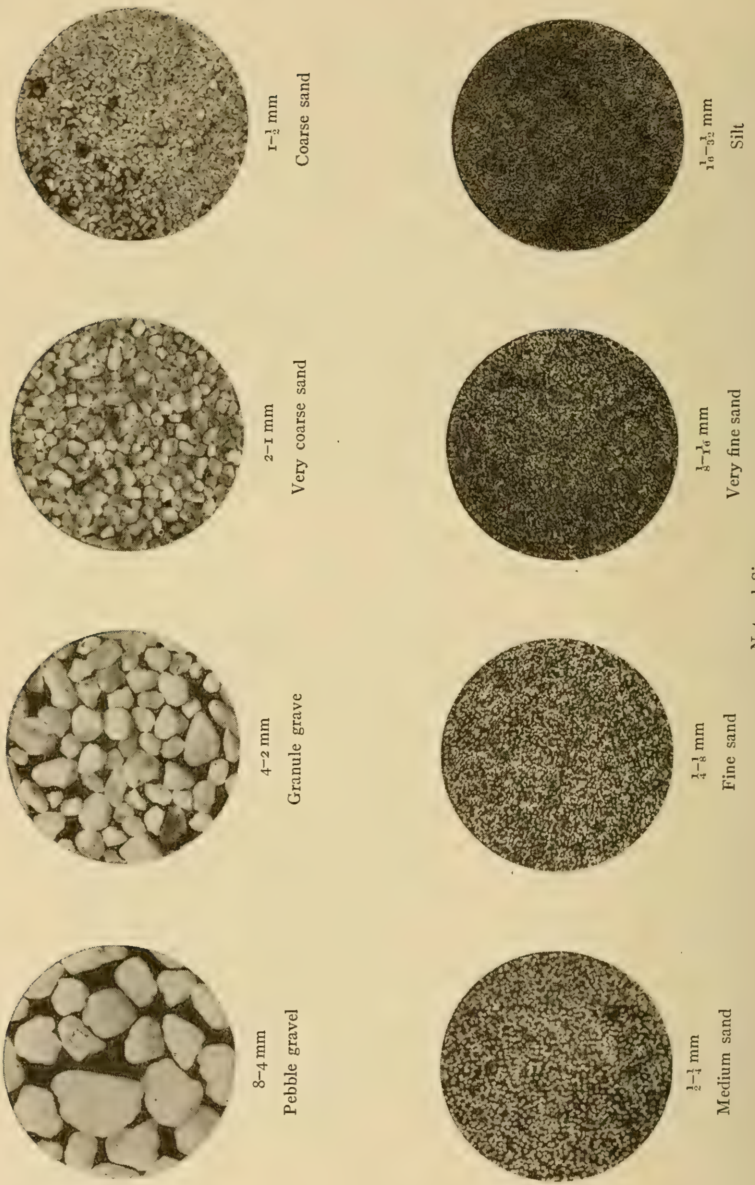
ROCK TERMS

Conglomerate.—There are certain terms which are used with greater uniformity and less abuse than others. One of these is conglomerate. This term is very widely applied to rocks which are the consolidated equivalents of gravels. It is applied just as is the term gravel to rocks which vary widely in the sizes of their constituent particles. It seems desirable, therefore, to apply to it modifying adjectives as has been done with gravel, making the terms bowlder-conglomerate, cobble-conglomerate, pebble-conglomerate, and granule-conglomerate. The term granule-conglomerate is preferred to the term grit because grit has been used in England for both coarse- and fine-grained and angular-grained sandstones. The use of the term grit in the present sense seems therefore inadvisable.

Sandstone.—This term is generally used by geologists and no great change in its usage is here proposed. It is qualified by the adjectives very coarse, coarse, medium, fine, and very fine, and used for the consolidated equivalents of the various grades of sand. The term grit is not used for the coarser grade for the reasons stated in considering the term granule-conglomerate.

Siltstone.—After a consideration of a number of terms, siltstone was adopted by the writer as most acceptable for the consolidated equivalent of a silt. Shale, as proposed by some geologists, was considered objectionable because, in the usage of a majority of geologists at present, as well as etymologically, it is a structural term referring to the shelly structure of the rock rather than to the size of its grains.

Claystone.—The term argillite has already been used in another sense and the term shale is objectionable for the reasons given



Natural Size

FIG. 3

above. The term claystone is here proposed as most satisfactory for the indurated equivalent of clay, as defined above.

THE CLASS TERMS

The grade terms defined above for aggregates and for rocks are applicable, as the writer has pointed out in another part of this paper, to very few sediments of natural origin. Most such sediments are composed of particles of several or many grades and the names suggested above with definite numerical limits cannot properly be applied to them. This difficulty has been long recognized by students of sedimentary rocks and several schemes for meeting the difficulty have been proposed. Notable among these, because of the large amount of data published in accordance with it, is that of the United States Bureau of Soils which is given below.

CLASSIFICATION OF SOIL MATERIAL

United States Bureau of Soils*

Soils containing 20% silt and clay:

Coarse sand	more than 25% very coarse sand and coarse sand and less than 50% any other grade
Sand	more than 25% very coarse sand, coarse and medium sand, and less than 50% fine sand
Fine sand	more than 50% fine sand, or less than 25% very coarse sand, coarse and medium sand
Very fine sand	more than 50% very fine sand

Soils containing 20–50% silt and clay:

Sandy loam	more than 25% very coarse sand, coarse and medium sand
Fine sandy loam	more than 50% fine sand or less than 25% very coarse sand, coarse and medium sand
Sandy clay	less than 20% silt

Soils containing more than 50% silt and clay:

Loam	less than 20% clay, less than 50% silt
Silt loam	less than 20% clay, more than 50% silt
Clay loam	20–30% clay, less than 50% silt
Silty clay loam	20–30% clay, more than 50% silt
Clay	more than 30% clay

* C. C. Fletcher and H. Bryan, "Modification of the Method of Mechanical Soil Analysis," *U.S. Dept. of Agric., Bur. Soils, Bull. No. 84* (1912).

The scheme of class terms presented below was devised by the writer after a somewhat extensive consideration of several more complicated classifications. These were characterized by more extensive use of the adjectives coarse and fine and by the use of many combinations and permutations of several grade terms.

These were all rejected in favor of the simpler plan here presented because of the seeming futility of attempting to make detailed quantitative discriminations by use of a verbal scheme. Such discrimination can be satisfactorily made only by graphic or tabular methods and the writer believes the simpler classification will be most generally acceptable and therefore most useful in the study of sediments.

The table shows only class terms for aggregates; the proper rock terms will be chosen and used in an analogous manner.

Class Terms for Sediments

Specifications by Grade		Terms for Classes
Gravel > 80%		Gravel
Gravel > sand > 10%	Others < 10%	Sandy gravel
Sand > gravel > 10%	Others < 10%	Gravelly sand
Sand > 80%		Sand
Sand > silt > 10%	Others < 10%	Silty sand
Silt > sand > 10%	Others < 10%	Sandy silt
Silt > 80%		Silt
Silt > clay > 10%	Others < 10%	Clayey silt
Clay > silt > 10%	Others < 10%	Silty clay
Clay > 80%		Clay

Certain materials of sedimentary origin but highly variable composition, notably glacial till, will not fall into any of the divisions of the table above. No attempt has been made to make an all-inclusive scheme. Till is known by its extreme range of mechanical composition and by definition, therefore, will not fit into so simple a classification. The test of any classification is in its applicability to natural objects. The terms here proposed were tested by reference to a large number of analyses made by Udden.[1] By inspection of about fifty of these chosen at random it was found that only the analyses of till did not accord with the specification given for one of the terms, and that each of the other

[1] J. A. Udden, *loc. cit.*

sediments tested was assigned to a suitable name differing only in added exactness from that used in the original description. In the table below are given nine of these analyses showing the

TABLE OF MECHANICAL ANALYSES BY J. A. UDDEN* SHOWING THE SEDIMENT NAMES APPROPRIATE TO THE CLASSIFICATION OF THIS PAPER

Diameter in Millimeters	No. 75† Gravel †	No. 9 Sandy Gravel	No. 18 Gravelly Sand	No. 16 Sand	No. 68 Silty Sand
64–32	....	.2	....	....	....
32–16	....	14.0	....	....	....
16–8	3.3	13.2	....	....	....
8–4	65.9	20.0	6.1	....	....
4–2	26.0	14.4	7.4	1.7	.2
2–1	3.0	11.4	3.6	24.4	.3
1–1/2	.3	18.2	7.2	49.2	7.2
1/2–1/4	.2	5.6	36.8	8.3	17.9
1/4–1/8	.7	2.6	37.4	14.8	48.7
1/8–1/16	.3	.2	1.2	1.0	8.4
1/16–1/32	....	....	.2	.4	13.2
1/32–1/64	....	....	....	.1	3.2
1/64–1/128	....	....	....	....	.7
1/128–1/256	....	....	....	....	.1

* J. A. Udden, *loc. cit.*

† The numbers are those used by Udden in describing these sediments. The names are applied by the author of this paper according to the terminology here presented.

Diameter in Millimeters	No. 70 Sandy Silt	No. 129 Silt	No. 131 Clayey Silt	No. 19 Silty Clay
2–1	....	....	....	....
1–1/2	.2	tr.	tr.	....
1/2–1/4	.9	tr.	tr.	....
1/4–1/8	11.9	tr.	.4	2.3
1/8–1/16	9.8	3.1	5.3	2.0
1/16–1/32	28.7	12.4	13.2	5.6
1/32–1/64	40.6	37.2	28.2	13.2
1/64–1/128	5.9	24.6	31.1	26.4
1/128–1/256	1.5	9.6	11.7	19.8
1/256–1/512	.2	3.5	6.4	17.8
1/512–1/1024	....	.9	2.4	10.0
1/1024–1/2048	....	.2	.8	2.3

composition, the number in Udden's table, and the name according to the present classification.

It will be pointed out that in order to name a sediment, one must first make a mechanical analysis. This is true to the degree

that it is true that microscopic study precedes the final naming of an igneous rock. However, as in the case of igneous rocks, field names based on simple megascopic inspection will be extensively used before detailed studies are made. It is believed that field names can be more accurately and expressively used if the principles and essential facts of a quantitative classification such as that here proposed are duly recognized.

THE PRE-CAMBRIAN OF WESTERN PATRICIA[1]

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The purpose of this paper is briefly to summarize the results of two seasons' field work in western Patricia. Patricia lies in the extreme northwestern part of the province of Ontario, north of the Winnipeg, English, and Albany rivers, and their expansions, Lac Seul and Lake St. Joseph. The areas studied by the writer lie in the southwestern part of the district, and in a sense intervene between the classic areas studied by Lawson and others around the Lake of the Woods and Rainy Lake and a number of areas in the province of Manitoba, more recently studied by Bruce, Alcock, Moore, and others. Reconnaisance work had already been done in the Lac Seul region and northward along the Trout Lake, Wennasaga, Cat Lake, and other rivers by Dowling, A. W. G. Wilson, Camsell, and others, and the work of E. S. Moore in the region southeast of Lake Winnipeg had extended in a few places across the boundary of Manitoba into Patricia. The writer's work was done under the direction of the Department of Mines of Ontario in the Lac Seul region in 1919 and along the Ontario-Manitoba boundary from the Winnipeg River northward in 1921. No great originality or finality is claimed for the results as the work in both cases was confined to narrow strips of country immediately adjacent to the survey-lines or rivers which were traversed, and was not of such a nature as to allow of much areal mapping, which would afford a more complete knowledge of the relationships of the various formations than is possible by reconnaisance methods. There has not been time for microscopic study of the rocks in the boundary region, but their general character is evident and in most cases they have been determined already with accuracy by Moore, so that data are now available for at least a tentative

[1] Read at the Toronto meeting of the American Association for the Advancement of Science.

discussion of the relations of the two areas with one another and with the surrounding regions.

Lawson's general statement of the geological sequence of the Lake Superior region is as follows:

Algonkian	Keweenawan Unconformity Animikie	
Eparchaean Interval		
Archean	Algoman granites, gneisses, etc. Irruptive contact Upper Huronian Unconformity Lower Huronian Unconformity Laurentian granites, gneisses, etc. Irruptive contact	
	Keewatin Coutchiching	Ontarian

The Algonkian formations need not concern us for the purposes of this paper, although dikes exist in some of the areas considered which may be of Keweenawan age.

The region around Lac Seul and northward as interpreted by the writer from data collected in 1919 includes the following geological sequence:[1]

4. Younger porphyritic granite (Birch Lake River).

3. Older red and gray, sometimes gneissoid granites.

2. Upper sedimentary and schist series, including a (basal?) conglomerate, hornblende schist and other schists and possibly limestones and quartzites.[2]

Lower volcanic and schist series, including more or less altered volcanic rocks of rhyolitic, andesitic, and basaltic types, frequently ellipsoidal in structure, hornblende schists, in part ferruginous, and some jaspylite.

1. The lowest member of this succession is correlated with some confidence with the Keewatin of Lawson on account of its litho-

[1] But see the *Report of the Department of Mines of Ontario*, Vol. XXIX, Part 1 (1920), p. 181, for an alternative classification.

[2] The two last were not seen by the writer. See C. B. Dowling, *Geol. Surv. Can.*, Vol. VII, Part F.

logical resemblance, and because it is the oldest rock-formation present and antedates all of the granites with which it is in contact. Tentatively, however, the local name "Lac Seul Series" may be applied to it.

2. The series above the volcanics appears to be of predominantly sedimentary origin, with a basal conglomerate which has a

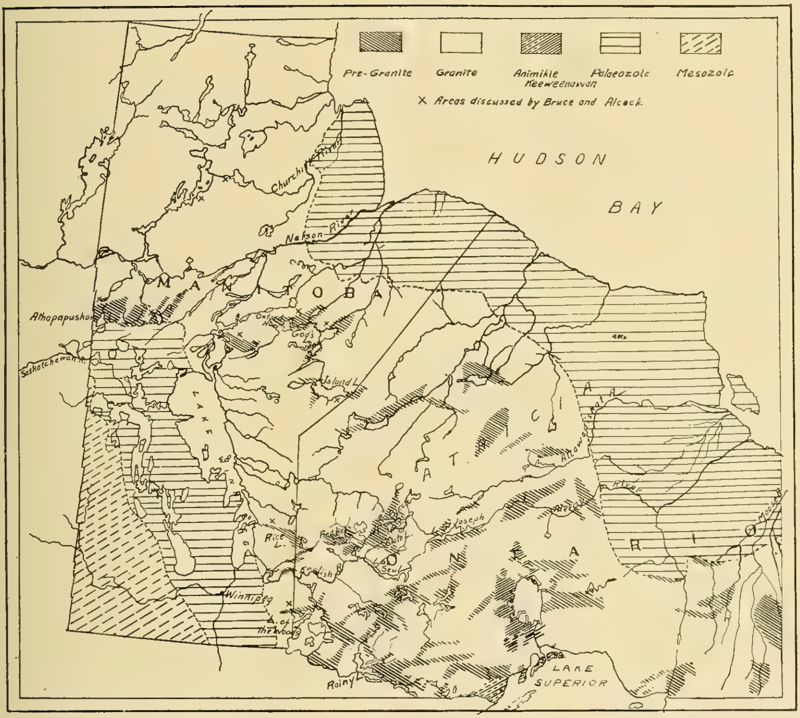

FIG. 1.—Map indicating pre-Cambrian areas mentioned in this paper

rather wide extent. It was observed especially at Slate and Birch lakes and was also reported by Dowling at Red Lake. In all three localities it is of practically identical lithological composition. Following Moore's example in the case of a similarly related series in eastern Manitoba, it was assigned to the Lower Huronian.[1]

[1] See *Ont. Dept. Mines Report*, 1920, p. 181, and compare *Geol. Surv. Can. Summary Report*, 1912, pp. 262 ff.

However, it affords no evidence of this so far as examined either by lying unconformably on post-Keewatin granites or by the presence of granite pebbles in the conglomerate. Therefore, its assignment to the Lower Huronian would imply either (1) that the granites of this region are all of post-Lower Huronian age, or (2) that the denudation of the great erosion interval which followed, or accompanied and followed, the intrusion of the Laurentian batholiths, was not here enough to uncover the batholiths before the Lower Huronian sedimentation began. If batholithic intrusion took place here in Laurentian time, the batholiths were not uncovered until much later perhaps between the Upper and Lower Huronian or even during the Eparachaean interval. Of these two alternatives, the second appears to the writer to be the less probable, judging by comparison with other regions not far distant. Neither alternative would demand the complete absence of Laurentian granite pebbles, since these might have been transported from a distance, and the quartz pebbles, which occur and which are well rounded in contrast to the angular chert-pebbles of Keewatin origin, probably are the residuals of such traveled material. For this series the name of "Birch Lake Series" is suggested.

3. The granite bodies which were observed in intrusive relations with the Lac Seul (Keewatin) series only are in two cases pink to grayish pink in color. In some parts, usually near contacts or where inclusions of older rocks are abundant, they display a gneissoid texture; in the central parts of the exposed areas and where relatively free from inclusions they are more massive. They are also in parts porphyritic. The rocks with which they are found in intrusive contact are frequently cut by dikes of pegmatite, while aplitic dikes as well as pegmatite occur within the mass of the granite itself. The rock is biotite granite with some hornblende, micropegmatite, and microcline, but no muscovite, tourmaline, or titanite. Another type of granite observed in intrusive contact with both the lower (Lac Seul or Keewatin) and upper (Birch Lake) schist series, is of gray color and is practically a binary granite with microcline as the chief feldspar. It also contains a little tourmaline, some oligoclase or andesine, and a little zircon and garnet. In the pegmatite dikes which accompany this granite tourmaline and

muscovite are largely developed. This type of granite occurs on the Wennasaga River from a point about ten miles above Slate Lake to Hailstone Lake, and also on Pakwash and Little Shallow lakes, where it has a syenitic phase with very little quartz. The same intrusion may be represented by dikes on a small island near the outlet of Lac Seul, which are composed of mica diorite.

Granites and gneisses of the red type were observed to the south of South Cove, Lac Seul, on the lower Wennasaga River, in the Cat River basin from Big Portage Lake to Springpole Lake, and on the lower Woman and Trout Lake rivers.

The relations in age between these two types of granite were not observable on the route followed by the writer. Both are post-Keewatin. The gray type is later also than the upper schist series, and both may be. If one is Laurentian and the other later, say Algoman, the Algoman is the gray granite.

There is, in addition, a coarsely porphyritic red granite intrusive in the red granite-gneiss of the Birch Lake River. It was not seen in contact with the schists, either upper or lower. This porphyritic granite is distinguished from the others by the presence of accessory titanite.

We pass now to the area studied during the summer of 1921 which lies along the Ontario-Manitoba boundary, a north and south meridian line, and is on the average about seventy-five miles (from sixty to one hundred) west of the field already described. Here we find as the oldest constitutents of the complex two series of rocks quite similar lithologically, and in their stratigraphic relation to each other, to the two series of schists already described.

1. The lower is a predominantly volcanic series which includes[1] greenstone (massive diabase and ellipsoidal lavas), quartz-porphyry, rhyolite, trachyte-felsite, green and gray schists due to alteration of these, and in one place a bed of white quartzite, partly iron-stained which occurs on the south side of the Winnipeg River a little west of the boundary, and has a total thickness of about thirty feet. To these rocks the name "Rice Lake Series" was given by Moore.

[1] E. S. Moore, *Geol. Surv. Can. Summary Report*, 1912, pp. 262 ff.

2. Lying above this is a predominantly sedimentary series whose most important rock is an extensive and thick conglomerate composed of the materials of the lower series with the exception of two constituents, a granite which does not appear within the area examined by Moore, and cherty fragments from iron-formations which were also not found in the lower series, although similar rocks are found in the upper series itself. These cherty fragments may have come from portions of the lower (Rice Lake) series since removed by erosion, or from parts farther east where they are known to occur in the lower series. There is a possibility that a gray gneissoid granite which may be seen on the Winnipeg River intruding the Rice Lake series may account for the granitic pebbles in the conglomerate. This gneissoid granite was not found in intrusive contact with the upper (Wanipigow) series and is older than the red and grayish-yellow or white binary pegmatitic granites which occupy most of the region, since these granites and the pegmatites derived from them intrude the older gray granite, and the red granite contains inclusions of it which, in many observed cases, have themselves included xenoliths of the Rice Lake (Keewatin) series. But while this is conclusive as to the relative ages of the various granites and the volcanic series, it is not conclusive as to the relative ages of the gray granite and the upper or Wanipigow series. The Wanipigow may then be older than any of the local granites and the pebbles found in its conglomerates may have been transported from a distance.

Comparing the Wanipigow conglomerate with that found in the upper or Birch Lake series of the Lac Seul region, it is true of both that they consist largely of pebbles derived from the volcanic rocks which immediately underlie them. Both also contain fragments of chert and jasper, which can be accounted for by the presence of iron-formation in the lower series of the eastern field, but are absent in that of the western area. In both, too, are pebbles of quartz. In the Lac Seul area these are hard to account for. They are well rounded and consist of a "sugary" white quartzite, partly stained to a yellowish color by iron oxide, which shows under the microscope "a granular texture of somewhat interlocking grains, no secondary enlargement of grains, slight amounts of bleached

biotite and brown iron oxide, very occasional grains of apatite and magnetite and flecks of kaolin." The quartz pebbles in the conglomerate on the interprovincial boundary are of a rather more glassy and massive appearance and must undoubtedly be described as vein-quartz. They cannot be accounted for as coming from the quartz veins which are now to be seen throughout the area, as these are of later age and owe their origin to the subsequent granite intrusions. But there is a bed of quartzite, as already described in the Rice Lake rocks, which outcrops on the Winnipeg River a little west of the Ontario-Manitoba boundary, and to this the pebbles of the conglomerate may in part be attributed, while others are no doubt derived from distant sources.

Taking everything into account there seem to be fairly good reasons for correlating the conglomerate horizons of the two areas and also the volcanics which underlie them, which may be taken as in all probability Keewatin. The conglomerate would then agree in age with the great erosion interval which has been found elsewhere after the Keewatin. In the region to the south and east, however, the extrusion of the volcanics, partly at least under water, was followed by mountain-building accompanied by granitic intrusion and denudation. In the area which is now under review there is no evidence of angular unconformity between the volcanics and the sedimentaries. The sedimentaries may have been largely subaerial in origin and in that case the history indicated is simply (1) emergence, (2) erosion of low-lying land to a surface of low relief, and (3) deposition of coarse materials perhaps on a piedmont plain. Some of these materials are of local origin while others (the quartzes, the cherts in part, and the granites) have been transported for greater distances.

A recent paper by Drs. Alcock and Bruce[1] sums up very well the results obtained from a study of a number of areas in northern Manitoba together with that studied by Moore to the southeast of Lake Winnipeg and the Star Lake area on the Ontario boundary farther south—in all ten localities. Their general conclusion is that the historical succession begins in most instances, as here, with very ancient volcanic extrusions. This was preceded in some cases by sedimen-

[1] *Bull. G.S.A.*, Vol. XXXII, pp. 267–92.

tation, as in the Rainy River region, "in others, sediments were interbedded with the volcanics, and in other areas these early periods of sedimentation continued long after the extrusion of lavas had ceased." In some cases a conglomerate exists which may mark an unconformity between the two divisions of this pre-granite series, as in the Lac Seul area; in others conglomerates occur at several horizons in the upper sediments, but some of them are not of great lateral extent, while graywackes and arkoses indicate little transportation or sorting and possibly subaerial deposition. In some places cross-bedded deposits are interpreted as ancient deltas.

The whole would agree with the hypothesis that while post-Keewatin mountain-building occurred in the Rainy Lake field and others farther east, the country to the north and west, although elevated above sea-level, remained in the condition of a piedmont costal plain and, not being folded, was not intruded by granites of Laurentian age.[1] At the same time it was covered with the ill-sorted products of mountain erosion, largely through the action of torrential streams. At a later time, however, this region was subjected to folding, batholithic intrusion, and subsequent deep erosion. This was followed in some localities by one or more periods of deposition with intervening folding and erosion, after which long erosion had produced peneplanation before the advance of the Ordovician sea.

This would agree very well with the facts observed by the writer, except that the later sediments following the first folding (Upper and Lower Missi, Churchill quartzites, etc.), do not occur in the region on which this paper is based.

[1] An exception to this is made in the case of the Athapapuskow area in northwestern Manitoba which would appear to limit the area in which the Laurentian may be absent on the northwest.

Petrological Abstracts and Reviews

CHARLES H. BEHRE, JR.

Ferguson, J. B., and Merwin, H. E. "The Melting Points of Christobalite and Tridymite," *Amer. Jour. Sci.*, XLVI (1918), 417–26, figs. 2.

A description of experimental methods employed in testing the melting points of these two minerals. A high-temperature furnace, built on the cascade principle, and capable of maintaining a temperature of 1700° for several hours, is described. By means of this furnace quartz has been inverted directly through dry heat alone. The melting point of tridymite has been determined (for the first time) as 1670°±10° C.; that of christobalite has been redetermined; it is 1710°±10° C. Christobalite is stable at higher temperatures than tridymite as determined earlier by Fenner.

Ferguson, J. B., and Merwin, H. E. "Wollastonite ($CaO.SiO_3$) and Related Solid Solutions in the Ternary System Lime-Magnesia-Silica," *Amer. Jour. Sci.*, XLVIII (1919), 165–89, figs. 8.

A further experimental study of the liquidus curves for the system of these three oxides, though not completely quantitative, yet confirms the earlier work with the same system, demonstrates the existence of solid solutions of diopside up to the amount of 16 per cent in pseudowollastonite and diopside, and of åkermanite in wollastonite and pseudowollastonite. A new compound—5 $CaO.2MgO.6SiO_2$—is reported. The paper contains also a fairly complete discussion of results obtained in the curves derived, and photographs of the solidus-liquidus concentration-temperature models.

Ferguson, J. B., and Merwin, H. E. "The Ternary System $CaO.MgO.SiO_2$," *Amer. Jour. Sci.*, XLVIII (1919), 82–123, figs. 19.

This is the most complicated system of any that can be constructed of three of the four oxides, CaO, MgO, Al_2O_3, and SiO_2. Försterite, diopside, enstatite, tridymite, cristobalite, lime, magnesia, pseudowollastonite, and two compounds of the three oxides were obtained. Solid solutions of five types were also recognized in crystalline form; these included clino-enstatite-diopside solutions, pseudowollastonite solutions of varying composition, wollastonite solutions, solutions of an unnamed compound of the three oxides, and menticellite solu-

tions. Scholler's åkermanite could not be prepared, but $5CaO.2MgO.6SiO_2$ and $2CaO.MgO.2SiO_2$ were recognized for the first time. The tridymite-cristobalite inversion temperature is essentially 1470° C., but measured with difficulty because of the great sluggishness of the inversion.

FERGUSON, J. B. "The Oxidation of Lava by Steam," *Jour. Washington Acad. Sci.*, IX (1919), 539–46.

Demonstrates experimentally that the formerly generally supposed oxidizing power of steam in lavas is not effective. Hence volcanoes may give off lava bearing ferrous iron and yet discharge large amounts of steam.

FLÖRKE, WILHELM: *Über die kunstliche Verwitterung von Silikatgesteinen unter dem Enfluss von schwefliger Säure.* Giessen, 1915. Pp. 32.

This is a study of the action of sulphur dioxide on coarse-grained igneous rocks. Experiments were carried on in the presence of water. All types of rock, varying from granite to gabbro, were attacked by the SO_2 vapors. The ferro-magnesian minerals were most corroded, hence the basic rocks also suffered most. Soluble sulphates of aluminum, iron, manganese, calcium, magnesium, sodium, and potassium were produced, as well as insoluble hydroxides of aluminum and iron.

FOYE, WILBUR GARLAND: "Geological Observations in Fiji," *Proc. Amer. Acad. Arts and Sci.*, No. 1, LIV (1918), 1–145, bibliography, figs. 40, pls. 1; in two parts.

A summary of the geology and petrology of the Fiji Islands is here presented. The group consists of two larger islands, Viti Levu and Vanua Levu, having central cores of deeply eroded plutonic rocks and possibly representing an earlier continental mass, and of several smaller fringing land masses. Four periods of vulcanism are recognized, the first being rhyolitic, the last basaltic, and the two intermediate ones andesitic. On Viti Levu a series of Miocene (?) sediments is much folded and overlain on the coastal plains by gently dipping post-Tertiary beds. On Vanua Levu are Pleistocene or recent coastal plain limestones and volcanics. Here subsidence has been generally accompanied by reef formation. An extended discussion of the coral reef question is given and a modification of Darwin's hypothesis thought to be favored in some measure.

The history may be summarized as follows:

9. Subsidence.
8. Basaltic intrusions and extrusions.
7. Uplift and erosion of (6).
6. Subsidence, with the deposition of about 150 feet of limestones and marls.

5. Second period of volcanic eruption, with subsequent erosion.
4. Uplift and erosion of (3).
3. Subsidence and deposition of limes, sands, and clays.
2. Andesitic lavas extruded, later eroded.
1. Plutonic intrusives, eroded to late maturity.

The first part of the paper describes the general geology of the islands; the foregoing is a brief summary. The second part discusses the petrography of the region studied. The important sediments are chiefly calcareous, but some conglomerate is known—river gravel, with bowlders of all sorts, and a calcareous conglomerate with over 50 per cent igneous bowlders but much shell-waste in the cement. The igneous rocks described are chiefly andesites and basalts, of which the latter preponderate in the descriptions.

Some of the extrusions were submarine, marked generally by the presence of hornblende; this character almost appears to be diagnostic of the subaqueous origin of such flows as bear it. Another interesting feature is the persistent association of hypersthene and hornblende.

The first andesitic period is recognized only on the two large islands. The flows of the second andesitic period are widespread and may be essentially synchronous in origin with some basalts and rhyolites. The lavas of the basaltic period, again, are more limited in their distribution. In general, differentiation in Fiji progressed from acid to basic. Volcanic vents have been singularly persistent, the basaltic flows seldom or never forming cones of their own. Ten rock analyses are presented, but no modes are given and only a few of the rocks are classified according to the norm system.

GOLDSCHMIDT, V. M. *Die Gesetze der Gesteinsmetamorphose, mit Beispielen aus der Geologie des Südlichen Norwegens.* Christiania, 1912. Pp. 16, fig. 1.

A concise application of the laws of thermodynamics to metamorphism. The "mineralogical phase rule" states that in a stable combination as many minerals may be formed as there are variables in the system. Thus in a mixture of silica, magnesia, and alumina only three minerals may be developed. The conditioning agents in contact metamorphism are pressure and temperature. By plotting the pressure horizontally and the temperature vertically, various fields are obtained which are either gradational or sharply marked off from each other. The melting temperatures of the more refractory minerals limit the phase-curve above. The effect of pressure is well illustrated by grossularite, which requires a higher pressure to maintain its identity at high temperatures than at low ones; its compact atomic structure is also favorable to stability at high pressures. Separate curves for each system may be prepared by applying the third principle of thermodynamics, Nernst's theorem; the approximate formula used in calculating the curve is from the same investigator. Such a curve applied to the system $CaO.SiO_2.CO_2$ yields a change

from calcium carbonate and quartz at lower temperatures (mean about 900° C.) to wollastonite and carbon dioxide. This and similar rules are exemplified by the crystalline schists of the Christiania region.

GOLDSCHMIDT, V. M. *Das Devongebiet am Röragen bei Röres.* With a paleontological supplement: NATHHORST, A. G. *Die Pflanzenreste der Röragen-Ablagerung.* Christiania, 1913. Pp. 27, pls. 5, maps 2, figs. 3.

This is a report on the areal and structural geology of an area measuring about 10 by 7 kilometers in south-central Norway, bounded on the north by the Lake of Betnen, on the south by the Lake of Feragen. The sedimentaries shown here are Cambrian, Ordovician, and Devonian, the last composing by far the greater part. Granite, augen-gneiss, saussuritized gabbro, and basic peridotite-serpentines are the igneous rocks. Chromite has been mined in the last-named rock. The Devonian beds overlie unconformably the eruptives and older sedimentaries; they consist of conglomerates, sandstones, and slates. An especially interesting member of the Devonian sequence is a 200-meter-thick serpentine conglomerate, of which the angular bowlders resemble breccia-fragments of serpentine; at its base it goes over locally into white magnesite. The total thickness of the Devonian is about 400–500 meters.

Faulting has affected the pre-Caledonian sediments, and this was followed by a period of intrusion from which date the eruptive rocks mentioned above. The pre-Devonian beds dip toward the northwest.

Devonian beds, however, have a general southeasterly dip. These sediments were probably deposited in a basin or basins of limited extent, formed and filled during the middle Devonian.

Illustrative plates and a brief description of the Devonian floras of the region accompany the report.

GOLDSCHMIDT, V. M. "Über einen Fall von Natronzufuhr bei Kontaktmetamorphose," *Neues Jahrb.*, XXXIX (1914), 193–224, pl. 1.

A study of contact metamorphism in sandstones of Norway. The unmetamorphosed sandstones are somewhat arkosic (microperthite, albite, orthoclase, and microcline are the feldspars) and flakes of muscovite and chlorite are also present; the matrix is calcareous or argillaceous. These sandstones are Devonian or Silurian in age. When metamorphosed they normally become biotite-rich quartzite or even hornfels. Wollastonite is commonly developed. In other instances secondary potash feldspars, sometimes intercrystallized with plagioclase, appear in the matrix. Besides quartz, a pyroxene (hedenbergite) is very common. This description characterizes the normal type of metamorphism.

An entirely distinct type of metamorphism, common along the borders of pegmatite dikes, is conspicuous in the presence of aegirite and riebeckite, as well as of long, needle-like titanite crystals. The latter, as well as the soda-rich pyroxene and amphibole, are attributed to an increase in soda-content, with a corresponding decrease in calcium oxide. The formation of aegirite and riebeckite takes place especially in the absence of alumina.

GOLDSCHMIDT, V. M. *Geologisch–Petrographische Studien in Hochgebirge des Südlichen Norwegens: III, Die Kalksilikatgneise und Kalksilikatglimmerschiefer des Trondhjem-Gebiets*, Christiania, 1915. Pp. 37, pls. (and maps) 2, table 1.

This is a summary of investigations in the zone of the Gula gneisses and slates of the Trondhjem district, Norway. The Gula group is probably of Silurian age. The rocks are highly metamorphosed, and the particular facies here studied are those rich in calcium silicates. Several zones of the schists are recognized, varying in their chlorite and biotite content. The results of extreme metamorphism may be summarized as follows: (*a*) Highly calcareous rocks lose their biotite content, this being replaced by plagioclase, amphibole (or pyroxene), and potash feldspar; or, (*b*) If poor in calcium oxide, the rocks are converted into a biotite-plagioclase rich slate, with varying amounts of quartz. In the former case the rock texture and constituents vary markedly with variations in degree of metamorphism. The latter type may be readily shown to be of sedimentary origin by means of microscopic study, corroborated by chemical analysis. Methods given in the text for calculating the theoretical constitution of these meta-sedimentaries are most instructive.

GOLDSCHMIDT, V. M. *Geologisch-Petrographische Studien im Hochgebirge des Südlichen Norwegens: IV, Übersicht der Eruptivgesteine im Kaledonischen Gebirge zwischen Stavanger und Trondhjem*. Christiania, 1916. Pp. 140, pls. (and maps) 7, table 1, figs. 2.

Reports the petrologic findings in an area about 600 kilometers long lying between Stavanger and Meraker, in southern Norway. This area bears igneous rocks of all sorts, from acid to basic. It is impossible to treat these as though they were all products of a single magmatic province; more probably they belong to three separate groups, as follows: (1) Green lavas, tuffs, and intrusives—the differentiation products being chiefly basic; (2) Anorthosite-charnokite rocks, with numerous differentiation products; and (3) Tonalite-granodiorite magmas, with many differentiation products. Some few of the rocks, indeed, do not even fit into such a classification.

In the first group are lavas, tuffs, agglomerates, and dike-rocks. Pillow-lavas are common. The intrusives of this group are gabbros and olivine-rich rocks. These are often saussuritized, uralitized, or converted into serpentine. Analyses of members of this class, as well as of the two others, are presented. The green lavas probably range in time from the upper part of the Ordovician into the Silurian; they are apparently homologues of the greenstones of England and Wales, which, however, were extruded at a slightly earlier date.

The anorthosite-charnokite rocks vary greatly in character. Some are typical gabbros and norites, others bear a little potash feldspar. Uralitization is common here.

Masses of pyroxenites and peridotites also belong to this period; these generally appear as lenses enclosed in basic or intermediate masses of more recently consolidated magmas of the same group. Another type of rock found here is labradorite-rich, hypersthene-bearing "labradorfels" (=anorthosite). All the above rocks of this segregation group are basic. There are also norites and mangerites; hypersthene-syenites represent a gradation toward the more alkalic end of the series; and finally acid rocks are represented by granites—hypersthene-granite (birkremite), commonly showing droplet-like plagioclase within the potash feldspar, augite-granite, diopside-granite, aegirite-granite, amphibole-granite, and biotite-granite, the latter two forming the commonest acid rocks of the group. Pegmatites and dike-rocks are common, and the latter range from acid to basic (peridotites). The sequence in the anorthosite-charnokite group is known with certainty to be (1) pyroxenite-peridotite, gabbro and norite, (2) norite, mangerite, and labradorite, (3) pyroxene-syenite, monzonite, and granite.

These anorthosite-charnokite rocks appear to have played a noteworthy part in the diastrophism of the region. They are assigned to early Caledonian age.

The third group studied comprises pyroxenites, peridotites, and gabbros; intermediate rocks, too, such as diorites, hypersthene-mica-diorites, and a peculiar type newly called "opdalite," which appears to be essentially a quartz-diorite. The acid phase is represented by "trondhjemite," (new name) which Kjerulf calls an oligoclase-granite, and which might as well be characterized as a granodiorite. Associated with these rocks are some dike-rocks, which incline generally toward the acidic; thus trondhjemite-porphyries, -aplites, and -pegmatites are recognized. The porphyritic phases occur already as borders of the larger intrusive masses.

A noteworthy fact is the sharp boundary of these aplites against the schistose basic country rock. This is explained by applying the principles of differentiation through fractional crystallization. A granite which has differentiated and achieved stability through having the basic constituents of the mother magma crystallize out, cannot resorb similar basic components; a magma can only assimilate the country rock when the mineral constituents of the latter have not been previously lost by differentiation in the mother magma.

Most of the rocks of the trondhjemite character are laccoliths or laccolithic. They all appear to be post-Ordovician; they may be described in general as of Caledonian (Upper Silurian) age.

Many rocks do not definitely fit into any of the foregoing three groups. These include pyroxenites, gabbroid types, basic and normal diorites, tonalite, granites, and their aschistic and diaschistic differentiates. This group may, if the sequence be as given above, indicate progressive differentiation. They occur south of the Trondhjemfjord. Granites are found on the west coast, too, and here are definitely assignable to Caledonian age, but cannot be readily placed in a magmatic province. Some augengneisses are also assigned to the same period.

As to the consanguinity of the three main groups recognized above, nothing definite can as yet be stated; surely the relationship is not as close between the separate groups as within each group. Each group, however, illustrates beautifully the differentiation-parallelism of separate magmas. Whether or not they *are* related might perhaps be answered by calculating the general composition of each group from a study of the rock-components. Data for such a calculation is, in the opinion of Doctor Goldschmidt, not yet sufficiently complete to undertake any generalizations. This is unfortunate, for here is a large geographic province which might furnish the best of examples for a study of magma-relationships and petrographic provinces in time if not in space.

Rocks similar to the green lavas occur in Scotland, and others like the Bergen-Jotun-granites (Group 2, above) are recognized from Sweden. The third group (called by Goldschmidt the opdalite-trondhjemite group) is undoubtedly represented in southern Scotland by the Galloway granite of Peach, Horne, and Teall, the age of which is less than the Ludlow and greater than the Old Red.

The writer seeks to draw analogies between the petrographic character of the rocks in the Stavanger-Trondhjem district and those elsewhere, especially in the Alps.

Twenty-two analyses of typical representatives of the several groups are appended, and many more, sometimes recalculated, are incorporated in the text.

GOLDSCHMIDT, V. M. *Geologish-Petrographische Studien im Hochgebirge des Südlichen Norwegens: V, Die Injektionsmetamorphose im Stavanger-Gebiete.* Christiania, 1921. Pp. 142, pls. 15, map (with separate legend) 1, with numerous tabulated analyses.

The rocks in this district are of several periods. At the base of the section are pre-Cambrian rocks, unconformable below Cambro-Silurian deposits. The latter consist of phyllites of Cambrian and lower Ordovician age and of green slates of the upper Ordovician and Silurian. These are followed by eruptives

of Caledonian age, which are partly green lavas, partly members of the opdalite-trondhjemite group discussed in a previous paper. Locally on the borders of the district are conglomerates, arkoses, and sandstones essentially of Downtonian age (Upper Silurian). Still younger dikes of diabase traverse the other rocks, and Quaternary sands and clays, partly glacial, are the last deposits to be laid down.

The pre-Cambrian rocks are chiefly granitic, with lesser amounts of amphibolites. Structurally they represent a major syncline, the axis of which parallels the trend of the Caledonides, i.e., runs northeast-southwest. The phyllite division of the Cambro-Silurian is definitely assigned to the Cambro-Ordovician on the basis of fossils occurring outside the area; it begins with a basal conglomerate, and passes into phyllites and calcareous strata, with local increase in sandy content. This phyllite division is at least 300 meters thick.

The green saltes are assigned to the Silurian also on the basis of fossil findings. These "slates" bear sandstones and conglomerates (rarely) and considerable amounts of limestone and dolomite (which may have been derived metasomatically from limestones), but metamorphosed clayey deposits are predominant among the sediments. Eruptive rocks are highly metamorphosed, so that they cannot always be assigned with certainty to volcanic origin.

Sedimentary rocks are known from the Caledonian; they consist of conglomerates, typical sandstones, arkoses, and similar types, derived largely from the pre-Caledonian and Caledonian effusives. Hence also these actually follow the Caledonian opdalite-trondhjemites and green lavas. A description of the first of these two Silurian types is to be found in the preceding review; both basic and acid rocks are known, the latter including adamellite, granite, and quartz-pegmatite.

The Cambro-Silurian rocks were deposited on a peneplained surface. This period of sedimentation was followed by one of intrusion—that of the opdalite-trondhjemite group, either synchronously with or slightly preceding the Caledonian mountain-building, during which sediments and intrusives alike were folded and fractured, the magmas perhaps being deformed even before complete congealing. Finally in late Caledonian times there was extensive faulting of all the rocks of the Stavanger District.

A study of the opdalite-trondhjemite masses of Stavanger demonstrates that the larger intrusives are limited to the boundary between the phyllites and the overlying green slates. These actually represent one type of structure, whereas an entirely different type is indicated by flat-lying masses of intrusives that seem to have been more severely displaced during cooling. In the Stavanger District the two types of structures, one representing igneous rocks cooled in place, the other those cooled after some dynamic action, lie close together; of these the distorted and "dynamo-transported" masses are by far the more common.

After this general discussion of the geology of the region, the writer proceeds to a description of the metamorphism that has affected the rocks, with special

regard for the injection-metamorphism that borders the opdalite-trondhjemite type of rocks. The clayey sediments have undergone regional metamorphism ranging in its products from the mere development of good cleavage, through the development of garnet-mica-schists, and finally the growth in these of basic plagioclase and of pyroxenes.

Most distantly from the borders of the acid masses the phyllite becomes altered to garnet; farther in toward the intrusive this is replaced by biotite, thus presenting an order that is the reverse of that more commonly observed. There is also a progressive increase in sodium content as the intrusions are approached. Closer yet microperthite makes its appearance. These rocks are in turn altered to injected mica-schists and gneissic mica-schists; the "injected" schists are not so in the sense that a liquid magma has been forced inward along the lines of schistosity; injection, as here used, implies rather a metasomatism, with a relatively small addition of extraneous material.

The upper Silurian green slates, too, form significant "injection schists." Even the basic differentiates in the opdalite-trondhjemite series have undergone some contact alterations, because affected by the later acidic intrusions.

Various types of metamorphic rock are described in detail; these include quartz-muscovite-chlorite-phyllite, quartz-muscovite-chlorite-garnet-phyllite, quartz-muscovite-biotite-garnet-phyllite, chloritoid-slates, and albite-porphyroblastic schists. Transitions between these and "augengneisses" are also known. When acid material is added by injection, the albite-porphyroblastic rocks are altered to injection-(injected)gneisses. These are partly bedding-plane injection types, with marked parallelism in the texture of the crystalline injected rock, partly vein-injected gneisses, and augen-gneisses (which are attributed also to injection of clay slates by the more acid rock).

Much of the alteration is due especially to the addition of quartz, water, and soda. These may have been brought in as soluble sodium silicate.

The metamorphism here described is compared with that elsewhere in Europe and also with that in the Christiania District, which has been studied in detail. In the latter instance it is interesting to note the far greater regional distribution of the contact phases, attributed by Goldschmidt to the greater water content of the effective magmas. In the Stavanger District probably the most conspicuous thing is the extensive contact metamorphism of *siliceous* sediments. Into the same class of metamorphism, due essentially to chemical differences between the country rock and the "magma milk," falls that described by Brauns under the name of "pyrometamorphosis."

GORDON, SAMUEL W. "Ordovician Basalts and Quartz Diorites in Lebanon County, Pennsylvania," *Proc. Acad. Nat. Sci.*, Philadelphia, Nov., 1920. Pp. 354–57, figs. 5.

Includes the first report of Paleozoic volcanic rocks in the form of a basalt flow, from Lebanon County, Pennsylvania. Intrusive into the Martinsburg

shale are sills and dikes of quartz diabase, to the northwest of which lie the interbedded basaltic flows. The quartz-diabase is a fine-grained dark greenish rock becoming very fine-grained at the contact; it may bear phenocrysts of augite, attaining a length of a centimeter; the texture is diabasic or ophitic, the labradorite being quite zoisitized.

The basalt is brecciated or tuffaceous and amygdaloidal, hence the flows were probably subaqueous; under the microscope the basalt breccia shows as a perlitic, dark greenish glass.

GUILD, F. N. "A Microscopic Study of the Silver Ores and Their Associated Minerals," *Econ. Geol.*, XII (1917), 297–353, pls. 11.

This paper represents a summary of rather extensive work done by Mr. Guild on silver ores from many localities, both here and abroad. The characteristic early minerals of silver deposits are pyrite, sphalerite, and arsenopyrite. These are chiefly hypogene in origin, though the first may also occur as a secondary mineral. They are commonly followed by the deposition of argentiferous galena and tetrahedrite; the order of deposition is arsenopyrite, pyrite, sphalerite, tetrahedrite, chalcopyrite, and galena. The later silver minerals that are discussed include stromeyerite, which exhibits exceedingly close "pseudo-eutectic" intergrowths, that may actually be eutectic in nature, pyrargyrite and proustite, stephanite, polybasite, argentite, and native silver. The latter certainly forms in some cases as a result of the breaking down of complex silver minerals. Other sources of silver are also briefly considered—cerargyrite and the rarer minerals huntlinite (silver arsenide), dyscrasite (silver antimonide), brogniardite (a complex sulphide of silver, lead, and antimony), and schirmerite (bismuth-silver-lead sulphide). Variously associated with the silver are chalcopyrite, bornite, chalcocite, and covellite. Commonly associated cobalt and nickel minerals are smaltite, niccolite, and breithauptite.

The predominant gangue minerals found with silver are carbonates—notably in the lead-silver type of ores; this indicates a tendency for such ore-minerals to come from neutral or alkaline solution, as carbonates could not be developed in acid solutions. The gangue minerals mentioned are calcite, dolomite, siderite, rhodochrosite and barite.

Excellent hints as to methods for distinguishing silver minerals microchemically are presented, a subject so far neglected only too often. Good manuals for the ore-geologist are indeed rare, and good manuals dealing with the microscopy of silver minerals are wholly lacking.

The paper contains interesting discussions of graphic intergrowth, of "enrichment" of silver ores, and of the composition of some important silver minerals. A table presents the investigator's ideas regarding the sequence of deposition of double salts of silver and other metals.

REVIEWS

Proceedings of the Coal Mining Institute of America. Thirty-third Annual Meeting, Pittsburgh, Pennsylvania, December, 1919. Pp. 158.

In an article on the "Future Development of Fuels," Henry Koeisinger, fuel engineer, United States Bureau of Mines, discusses those modes of coal consumption that utilize most fully the energy latent in the fuel, namely by-product production of coke, the use of powdered coal, and the use of so-called "colloidal fuel," a mixture of powdered coal and fuel oil. Electrification of railroads and better combustion of coal in the commoner methods of utilization come in for discussion.

Pages 34 to 43 are devoted to an excellently illustrated article by Reinhardt Thiessen of the United States Bureau of Mines, on the "Constitution of Coal through a Microscope."

Pages 89 to 101 are devoted to a paper by H. C. Ray, professor of ore dressing at the University of Pittsburgh, on "Modern Practices in the Washing of Coal," illustrated with nine text figures.

E. S. B.

Report on Some Sources of Helium in the British Empire. By J. C. McLennan and Associates. Canada Department of Mines, Mines Branch, Bulletin 31, 1920. Pp. 72.

Shortly after the commencement of the war, it became evident that, if helium were available in sufficient quantities to replace hydrogen in naval or military airships, the losses in life and equipment arising from the use of hydrogen would be enormously lessened. Helium, as is known, is most suitable as a filling for airship envelopes, in that it is non-inflammable and non-explosive, and, if desired, the engines may be placed within the envelope. By its use it is also possible to secure additional buoyancy by heating the gas (electrically or otherwise), and this fact might possibly lead to considerable modifications in the technique of airship maneuvers and navigation. The loss of gas from diffusion through the envelope is also less with helium than with hydrogen, but, on the other hand, the lifting power of helium is about 10 per cent less than that of hydrogen.

Early in 1915 Dr. J. C. McLennan, head of the department of physics in Ontario University, was requested by the Board of Invention and Research, London, England, to investigate the helium content in various natural gas supplies within the British Empire. As a result of these investigations it has been shown that the largest source of supply of helium at present known within the empire is located in Canada. Commercial methods of separating helium from the other components of natural gas were developed as a result of the preliminary investigations, and considerable progress was made toward the development of methods for the production of helium on a commercial scale, as a result of which it was shown that helium could be produced at a cost of somewhat less than $0.25 per cubic foot at normal pressures and temperatures.

As a result of a large number of analyses, which are given in this report, it was found that the richest natural gases in Canada contained about 0.33 per cent of helium—a percentage believed to be sufficient for profitable commercial extraction, but considerably lower than the percentages which characterize the gases from a number of wells in Kansas, where the helium content ranges from 1.5 to 2 per cent. Analyses are given of natural gases from Ontario, Alberta, and British Columbia.

As a supplemental investigation, a study was made of the radioactivity of a number of these gases. It was found that when the gases escape from the well they usually contain the emanations of radium and thorium. The thorium emanations are very short-lived, but the decadence in the radium emanations is much slower. Measurements of the radioactivity of a number of gases were made, the method used involving the deduction of the amount of radium emanation from measurements of the increase in electrical conductivity which the presence of radium emanations imparts to the gas.

E. S. B

Potash Recovery at Cement Plants. By ALFRED W. G. WILSON. Canada Department of Mines, Mines Branch, Bulletin 29, 1909. Pp. 34, pls. 10.

Considerable interest was awakened during the war by the cessation of potash imports from Germany in all possible substitute sources in the United States and Canada. The report under review is the outcome of investigations started then by the Canadian War Trade Board.

The wisdom of peace-time development of our slender resources of potash-bearing brines may be challenged. Much might be said in

favor of allowing such reserves to remain in the ground pending the next national emergency. But the recovery of potash as a by-product of cement manufacture and from iron-blast-furnace dust is utilization of raw material and of heat energy that otherwise would be wasted and should command the support of all conservationists. Such processes have the added advantage of minimizing the dust nuisance around cement plants, which is a danger to the health of employees and is detrimental to crops in agricultural districts. It has been estimated that in the United States, if all cement plants were equipped to recover potash salts, potash equivalent to over one-fourth of our normal imports of German potash salts could be recovered.

The report under review outlines briefly the principles underlying the recovery processes and describes in outline the equipments at all the plants in the United States and Canada where potash recovery has thus far been practiced. At the temperatures of 1,400 to 1,500° C. obtained in cement kilns, the potash-bearing silicates are in part decomposed, potash reuniting usually with the sulphate radical to form potassium sulphate, or to a lesser extent with the chloride radical to form potassium chloride—salts which are soluble and which pass into the stacks with the gases, where they can be recovered by spraying the gases or precipitating the dust by the Cottrell electrical process. The quantity of potash salts produced varies from 2 to 7 pounds per barrel of Portland cement.

Installation of potash-recovery equipment does not involve any changes in the processes of cement manufacture, nor does it affect the grade of the cement produced.

The report closes with a complete bibliography.

E. S. B.

Timiskaming County, Quebec. By M. E. Wilson. Canadian Geological Survey, Memoir 103, Ottawa, 1918. Pp. 197, pls. XVI, figs. 6, map.

This is a concise, detailed report of the results and conclusions of geological field work carried on for a number of years in Timiskaming County, together with a theoretical discussion of some of the more important problems of the area.

Timiskaming County has an area of approximately 20,000 square miles and lies on the east side of the boundary line between Ontario and Quebec and east and northeast of Lake Timiskaming. The National Trans-

continental Railway crosses the northern part of the county and this part can be easily reached.

This area lies within the Laurentian Plateau and is characterized by a remarkable uniform relief but the surface in detail is irregular. The minimum elevation is almost everywhere more than 800 feet, and the maximum less than 2,000 feet; thus the range in elevation is seldom greater than 1,200 feet. The northern part of the county is drained by the Bell and Harricanaw rivers flowing into James Bay, and the southern part by the head waters of the Ottawa River flowing into the St. Lawrence River.

A very widespread base-level represented by the erosion surface between the basal complex and the Cobalt series or other late pre-Cambrian formations is still preserved. So also is the peneplain developed before the advance of the early Paleozoic seas. Since these early Paleozic rocks are approximately horizontal, all the movements of this great area since that time have been due to regional uplift, warping, and faulting. Of these, faulting has been the most important.

Another very noticeable physiographic feature is the large number of linear valleys, which, when classified according to general direction, fall into three groups striking approximately northwest, north, and northeast. The evidence in favor and against the faulting hypothesis of origin for these valleys is given. The faulting hypothesis most easily accounts for these valleys, and is assumed to be the most reasonable explanation, although very little field evidence of faulting along the valleys has been found. These valleys are post-Silurian and pre-Glacial.

The rocks occurring in Timiskaming County fall into the following four divisions: (1) the basal complex, (2) the Cobalt series and associated intrusives, (3) the Ordovician and Silurian sediments, and (4) Quaternary Glacial and post-Glacial gravels, sands, and clays. Detailed lithologic descriptions are given of the many different rock types represented, with notes on the structure and origin of many of the metamorphic types. Based on lithology and origin, the rocks of this region may be grouped into three parallel belts running in a northeasterly direction. Sediments belonging to the Grenville series characterize the south belt; banded gneisses mostly of igneous origin, the central belt; and volcanics and clastic sediments, the Pontiac series, the north belt. In the southern part of Timiskaming County inclusions of Grenville sediments are found along the southern edge of the banded gneiss belt. Because of the many difficulties and uncertainties of long-distance correlation of very intensely metamorphosed pre-Cambrian formations outlined in chapter IV, no

attempt is made to correlate the Grenville sediments south of the belt of igneous rocks, with the Pontiac series north of this belt, although the three possible theoretical relationships are given.

Chapter VI deals with "Special Problems of the Timiskaming Region," a brief summary of the literature together with evidences and conclusions reached from a detailed study of this particular area. Conclusions are given concerning such problems as the "Origin of Pillow Structure," "Origin of Ferruginous Dolomite," "Origin of Banded Gneisses," "Origin of the Cobalt Series"; a general discussion of the "Clay Belt of Northern Ontario and Quebec," and the "Origin, Extent, and Duration of Lake Barlow and Lake Ojibway."

In chapter VII the gold, silver, and molybdenite prospects of the area are described. When this report was written none of these prospects was developed to the state of producing mines. The great mantle of post-Glacial lake clays which cover a large part of the county makes prospecting difficult.

In a brief review of this Memoir it is impossible to give an adequate summary of the many important problems of pre-Cambrian geology discussed. This Memoir will be found useful to anyone interested in the problems of pre-Cambrian geology of Quebec and Ontario.

J. F. W.

The Paleozoic Rocks of the Canton Quadrangle. By G. H. CHADWICK. New York State Museum Bulletin, Nos. 217, 218. Albany, N.Y., 1919. Pp. 60, pls. 12, figs. 3, maps 1.

Across the northern third of this quandrangle the Paleozoic rocks form the country rock, while in the southern two-thirds they outcrop as outliers among the pre-Cambrian rocks. These Paleozoic rocks are Upper Cambrian and Early Ordovician in age. A section from the base up is as follows: Potsdam sandstone and conglomerate (Cambrian) 0–150 feet, followed by a possible unconformity, then deposition of white sandstone 100 (?) feet, Theresa dolomite and sandstone 50 feet, and Heuvelton white sandstone 10–25 feet in thickness, all of which are Saratogan or Ozarkian in age. The Heuvelton is followed by a disconformity and after this period of erosion the Ordovician (Beekmantown) represented by the Bucks Bridge mixed beds of dolomite and sandstone 50–75 feet in thickness, followed by an unconformity and above this unconformity the basal 30 feet of the Ogdensburg dolomite. These various formations are described in detail. The Heuvelton and all beds above it are fossiliferous, but the fossils are poorly preserved.

The Potsdam sandstone is thought to represent the residuum of insoluble material from deep and thorough weathering of pre-Cambrian gneiss and quartzite. The total absence of fossils, the undercut erosion in the Grenville quartzite at some of the contacts, the fine and even nature of the sand itself right up to the contacts suggest a wind-blown origin. The position, the tillite-like nature, and many other features of some of the basal beds of the Potsdam suggest glacial deposits but no striated pebbles were found. The late pre-Cambrian and Cambrian history of this region is thought to have been as follows: (1) peneplanation, then (2) uplift and further deep weathering under a moist and warm climate, next possibly (3) glaciation followed by (4) arid, cold, desert conditions, and finally (5) slow submergence and encroaching of sea from the northeast. The late Cambrian and early Ordovician record is one of intermittent submergence and elevation. From the history of the region to the north it is almost certain that Chazy, Black River, and Trenton seas covered this area but their deposits have all been removed by erosion with the possible exception of a local thin bed of Trenton limestone. By the end of the Mesozoic the general region had been reduced to a peneplain. This peneplained surface is recorded by the high land with a nearly even sky-line. This peneplain was elevated, dissected by Tertiary rivers, and before Pleistocene glaciation, wide flat areas were developed which record a late Tertiary peneplain. The author calls attention to the close resemblance between the Mesozoic, Tertiary, and recent history of the region and the late pre-Cambrian and Cambrian history as outlined above.

J. F. W.

The Pre-Cambrian Rocks of the Canton Quadrangle. By James C. Martin. New York State Museum Bulletin, No. 185. Albany, N.Y., 1916. Pp. 112, pls. 20, figs. 30, maps 1.

The Canton Quadrangle lies in northwestern New York State about 12 miles east of Ogdensburg on the St. Lawrence River and 30 miles east of the Thousand Islands region. The geology is very similar to that of the Adirondack Mountains while the physiography is that of a line of foothills which mark the approach of the rugged interior to the southeast.

The oldest rocks, Grenville sediments, are crystalline limestone, garnet gneiss, quartzite, quartz-schist, and various other siliceous and pyritous gneisses. Owing to intense post-Grenville deformation no good continuous sections of the sediments remain, but the probable thickness is somewhere about two or three miles. The various rock

types of the series are intimately interbanded and in many cases one type gradually grades into the other. The dark-colored bands and spots rich in silicate minerals, in the crystalline limestone, are thought to represent recrystallized sedimentary matter and not to be due to the introduction of silica, iron, or alumina from the gabbroic or granitic magmas. Although some of the metamorphic amphibolite is of igneous origin and younger than the Grenville sediments, most of the field evidence points to a sedimentary or contact metamorphic origin for the garnet gneiss and a large part of the amphibolite. The different varieties of garnet gneiss and amphibolite associated with the igneous contacts probably are due to the different phases of intensity in the contact action.

The post-Grenville pre-Cambrian rocks are gabbro-amphibolite and granite gneiss intrusives. Two noncomformable contacts and their mineralogical composition indicate that certain of the amphibolites are igneous. The abundant inclusions of Grenville sediments in these amphibolites indicate their post-Grenville age. These gabbro-amphibolites are intruded by a gray to pinkish red massive to gneissoid granite gneiss. In almost all cases, owing to the severe regional deformation, the original nature of the contacts between the various types of pre-Cambrian rocks of this region is obliterated and it is very hard to work out field relationships. Inclusions of gabbro-amphibolites in pegmatitic phases of the granite gneiss prove a later age for the granite. Also during the intrusion of the granite magma, the amphibolite inclusions broke under deformation while granite flowed, which shows that the amphibolite antedates the intrusion of the magma. However, in only a very few cases is there evidence that these amphibolite inclusions are igneous and not metamorphic Grenville sediments. The great abundance of these inclusions, and the apparent incompetency of granite contact alteration to account for so much, suggests that much of it was formed by the gabbro-amphibolite intrusions before the invasion of the granite magma.

The rocks are almost universally foliated and over the whole area the foliation dips toward the west or northwest. A huge sigmoid fold in the southern part of the area is described and diagrammed in detail. Many minor folds are described.

This is an interesting description and application of a number of important principles of pre-Cambrian geology, especially the methods of separating the sedimentary and contact metamorphic amphibolite from the igneous gabbro-amphibolite, and the determination of the younger age for the granite as compared with the gabbro-amphibolite.

J. F. W.

Genesis of the Zinc Ores of Edwards District, St. Lawrence County, N.Y. By C. H. Smyth, Jr. New York State Museum Bulletin, No. 201. Albany, N.Y., 1917. Pp. 39, pls. 12.

This report presents the results of laboratory studies of ore from the zinc deposits of the Edwards district, which is about 15 miles south of the Canton area described in Bulletin 185, reviewed above, and the geology of the two areas is very similar. The ore minerals are sphalerite, pyrite, and galena, and occur as fillings of narrow cracks or as replacements along shear zones in the Grenville crystalline limestone. The deposits are of the high-temperature type, and the sequence of mineral deposition is as follows: (1) diopside, tremolite, (2) pyrite, (3) sphalerite, (4) galena, (5) talc, (6) serpentine. This sequence of mineral deposition indicates changing conditions from intense-contact, metamorphic conditions to those normal for the depths involved and without outside agencies. At all stages during this transition from intense to moderate conditions calcite was subject to repeated solution and recrystallization.

The granite magmas which intrude the Grenville sediments are considered the source of the ore minerals and during the cooling of the magma, gases and solutions were given off which carried the sulphur and metals into the country rocks where they were precipitated. The wall rock of the sphalerite is always crystalline limestone while the typical pyrite ore is always in schist or gneiss. Also the pyrite ore is always rich in graphite while the zinc ore contains but little graphite. The typical pyrite ore contains but little sphalerite but the zinc ore contains considerable pyrite.

These deposits are compared with zinc deposits of other regions and especially with the contact zinc deposits of the Christiania district described by Goldschmidt. Excellent photomicrographs show clearly the various mineral relations described in detail in the text. This is a valuable contribution to the subject of contact metamorphic ore deposits.

J. F. W.

New Edition of Coal, Oil, Gas, Limestone, and Iron Ore Map. West Virginia Geological Survey.

Thoroughly revised, showing oil and gas pools, many anticinal lines not heretofore shown, and also booklet giving the names and post-office addresses of all the principal coal-mining operators in West Virginia up to July 1, 1921. Scale, 8 miles to the inch. Price, folded in strong envelope and delivered by mail, $1.00. Remittances to West Virginia Geological Survey, Box 848, Morgantown, West Virginia.

Detailed Report on Nicholas County. By DAVID B. REGER. West Virginia Geological Survey, No. 31. 1921. 847 pages+xx pages of introductory matter; illustrated with 34 half-tone plates and 22 zinc etchings in the text, accompanied by a separate case of topographic and geologic maps.

Nicholas County contains the New River Coal Group, as also the Kanawha Group and the lower members of the Allegheny Series in its northern portion. This report contains a chapter on the "Paleontology of Nicholas County" and a short description of the chert deposits of West Virginia by Dr. W. Armstrong Price. Price, including case of maps, delivery charges paid by the Survey, $3.00. Extra copies of topographic map, 75 cents; of the geologic map, $1.00. Remittances to West Virginia Geological Survey, Box 848, Morgantown, West Virginia.

Geology and Mineral Deposits of a Part of Amherst Township, Quebec. By M. E. WILSON. Memoir 113, Canadian Geological Survey, Ottawa, 1919. Pp. 54, figs. 3, pls. VII, maps 2.

This district is thirty miles north of the Ottawa River and almost equidistant from Montreal and Ottawa, and lies within the dissected southern border of the Laurentian Plateau. The presence of extensive deposits of kaolin near the southern part of Amherst Township is of considerable geological interest, because kaolin is commonly thought to be the product of surface-weathering and in Canada, for the most part, the deposits formed by surface-weathering have been removed by Pleistocene continental glaciation.

The oldest rocks of this region belong to the Grenville sedimentary series and consist of quartzite, garnet gneiss, and crystalline limestone. These sediments are intruded by the Buckingham series of basic igneous rocks (gabbro, pyroxene diorite, and pyroxene syenite). Both the foregoing series are intruded by batholithic masses of granite-syenite gneiss. Glacial drift and marine Champlain clay partially fill the depressions between the rock ridges.

The kaolin and graphite deposits of the district are described in detail. The kaolin occurs in an extensive zone of fracturing and faulting in the Grenville quartzite and garnet gneiss and has been brought in by solutions from either above or below and deposited along open fracture planes or by the replacement of the quartzite wall rock. Crystals of tourmaline, a mineral formed at high temperatures, in the kaolin and the nearby outcrops of granite-gneiss suggest a deep-seated origin for

the kaolin. The presence of oxidized and kaolinized garnet gneiss at a depth of 85 feet is equally suggestive of the derivation of the kaolin from a superficial source. A summary statement of these two hypotheses to explain the origin of kaolin deposits is given, but the writer has no definite basis for deciding between them. The shattered zone of quartzite in which the kaolin occurs has a known width of 1,000 feet and a length of 7,000 feet. This kaolinitic quartzite rock can be easily crushed and is suitable for making silica brick of the ganister type or the kaolin can be washed from the crushed material and the quartz used for silica sand.

North of the kaolin locality a number of graphite deposits have been opened along the contacts of pegmatite, pyroxene granite, syenite, and Grenville limestone. The ore consists of aggregates of orthoclase, wollastonite, diopside, scapolite, and graphite. These relations and associations of minerals indicate that this material was formed by the interaction of emanations from the igneous intrusions and the limestone.

J. F. W.

Map of the North Pacific. By W. E. Johnson. U.S. Coast and Geodetic Survey, Map No. 3080, North Pacific Ocean; scale 1:20,000,000; dimensions 14 by 41 inches. Price 25 cents.

A new base map of the North Pacific Ocean on the transverse polyconic projection has been prepared by W. E. Johnson, Cartographer, of the U.S. Coast and Geodetic Survey of the Department of Commerce, and is now available for distribution. This system of projection was devised by Ferdinand Hassler, who was the organizer and first Superintendent of the U.S. Coast and Geodetic Survey. This projection was computed and constructed by C. H. Deetz, Cartographer, U.S. Coast and Geodetic Survey.

The Mogollon District, New Mexico. By Henry G. Ferguson. Bulletin 715-L, United States Geological Survey, Government Printing Office, Washington, D.C., 1921. Pp. 34, pls. 6, figs. 2.

The Mogollon (Mo-go-yohn) or Cooney district lies in southwestern New Mexico, about fourteen miles from the Arizona line. The district was discovered in 1875, when James Cooney found rich silver-copper ores there. Since then the mines have yielded about $16,000,000 worth of ores (estimated to 1917).

The topography is generally very rugged, especially on the eastern edge of the district, which lies along the Mogollon Range. The rocks are

dominantly Tertiary lavas, with interbedded sandstones. Faulting is extensive, and the fault fissures have been mineralized. In Quaternary times erosion was great and thick gravels accumulated; the gravel deposition was followed by more faulting, the fault plane paralleling the present front of the range, with downthrow on the west. Renewed erosion followed this last orogeny. The Tertiary formations, chiefly igneous, reach 8,000 feet in thickness. The flows are chiefly andesites and rhyolites, though there are a few basaltic lavas. Of the total thickness mentioned, 6,400 feet are pyroclastics and flows; the remainder are stream-laid sediments. Erosional unconformities within the sequence are common. Intrusives are represented by dikes of rhyolite and basalt.

Structurally the area is affected by complex normal faults; two periods of faulting are recognized—one before, the other after, the deposition of the rival gravels. The former was far more widespread, and nearly all the fault fissures of this period are now the site of fissure veins trending roughly north-south or northwest-southeast; one of these—the most prominent—can be traced for a length of seven miles, and the fault involves a displacement of a thousand feet or so. The first faulting resulted in increase erosion and the development of mature topography; on the west slope of the region there was at this time a broad valley, which later became filled with gravel to a depth of several hundred feet. Then came the great fault that now defines the front of the range; this renewed erosion and initiated the present cycle with its higher flat benches and lower steep canyons.

The ore deposits of the region are all in veins closely connected with the faults. The richest are the small ones lying along the fault fissures that are distributive from the great seven-mile fault (Queen fault) mentioned above. Locally the mineralization shifts from the main fissure to minor fissures in the wall, indicating that mineralization was not contemporaneous with the faulting. The mineral content of the veins includes quartz, calcite, a little adularia, and flourite (locally plentiful). Argentite, with small amounts of associated pyrite, chalcopyrite, bornite, galena, and sphalerite are the metaliferous primary minerals; in a few veins copper minerals—bornite, chalcopyrite, chalcocite, and tetrahedrite—predominate. Quartz and calcite are the chief gangue constituents. Oxidation is shallow and irregular. Sulphide enrichment appears to have been somewhat effective. The oxidized ore bears cerargyrite, native silver and gold, basic copper carbonates, limonite, copper pitch ore, cuprite, and manganese oxides. Chalcocite,

covellite, some argentite, pyrite, and native silver are probably due to sulphide enrichment, but a part of the argentite and pyrite and all of the bornite, chalcopyrite, tetrahedrite, and galena are apparently primary.

Quartz was the first mineral to be deposited and it was followed at once or even accompanied by the greater part of the sulphides. The later stages of vein-filling were marked by coarsely crystalline calcite, largely manganiferous and barren of sulphides. Mineralization of the wall rock is not prominent; in andesites, pyrite has penetrated the rock for short distances from the veins, or the rock is cut by veinlets of quartz, calcite, and copper sulphides. The dark silicates in the andesites are often almost completely altered, and calcitization is common. The rhyolitic country rock near the veins shows some secondary silicification, and the feldspars are frequently replaced by quartz with an apparent decrease of volume.

Although the oxidation zone is generally shallow, it may extend to the 500- or 700-foot levels. Argentite appears here and there as filling in minute cracks, apparently later than the veins, and pyrite clearly of later origin is seen in fissures in the quartz. No sulph-arsenic or sulph-antimony salts of silver, such as commonly characterize many sulphide enrichment zones, are found, but chalcocite and a small amount of covellite do attest the effectiveness of some enriching action. Probably sulphide enrichment is appreciably active only where unusually favorable conditions, such as later faulting, were present. The ground water-level lies very deep and the mines are dry, except along the Queen fault.

The ore shoots are 300 to 600 feet in drift length and about as long parallel to the dip, with widths averaging 5 to 15 feet. They tend to show flat bottoms, which is thought by the investigator to be suggestive of enrichment.

The peculiar localization of the productive veins within a small district not over one square mile in extent is attributed to the faulting, which only produced the throw necessary to bring the ore within reach of the surface over a very small area; greater or lesser throws either resulted in too deep an erosion or in the exposure of the barren low-temperature manganiferous-calcite veins.

The important mines are the Cooney, Little Fanney, and Last Chance; the last being the largest. In the past twenty-five years the Last Chance mine has yielded about $7,500,000, worth of ore. The metals obtained are gold and especially silver, and a high-grade ore lies close to $20 a ton in value.

C. H. B., Jr.

Tungsten in 1918. By FRANK L. HESS. From "Mineral Resources of the United States," (United States Geological Survey), 1918. Part I, pp. 973–1026; Government Printing Office, Washington, D.C. Pp. 53; with summary of recent publications.

The years 1916, 1917, and 1918 recorded the largest production of tungsten ores which this country has known, about 5,000 or 6,000 short tons for each of these years as compared with a maximum around 2,000 tons in previous years. Slightly over 50 per cent of the 1918 output was scheelite from California and Nevada, and nearly 40 per cent was ferberite from Colorado. Preliminary figures for 1919 and 1920 issued by the United States Geological Survey show a slump in production to around 200 to 300 tons, figures lower than any recorded since 1903 and due to the depression in the steel industry which is the principal tungsten consumer.

No fully satisfactory substitute for tungsten in tool-steel has been developed. To quote Mr. Hess: "It is said that in England and France molybdenum has been used to replace about half of the tungsten in some high-speed tool-steels, but it is apparently not a preferred metal, being used only when it is difficult to obtain tungsten."

In California and in Nevada scheelite is found mainly in contact metamorphic deposits in limestone near granitic intrusives. In South Dakota the production was mainly wolframite from replacement deposits in dolomite near Lead and Deadwood. The chief competitor for the American market is China, where the discovery of great, easily worked placers in the southern provinces has been the most striking event of recent years in tungsten geology.

A brief summary of the international situation shows that Great Britain controlled and imported, in 1918, 33.7 per cent of the world's output, and thus owned by far the greater part of the 1918 production.

Another interesting fact in regard to tungsten minerals is their rather general limitation in economically important deposits (with the exception of those on the Iberian Peninsula) to areas closely contiguous to the Pacific Ocean—a good illustration of the provincial character of metallic distribution, which may perhaps be correlated with the petrographic provinces as pointed out by Alfred Harker.

The paper presents an excellent and much-needed summary of the tungsten situation, treated both from the geological and economic point of view, and closes with a summary of recent literature on tungsten.

E. S. B. AND C. H. B., JR.

Geology of the Matachewan District, Northern Ontario. By H. C. Cooke, Memoir 115, Canada Department of Mines, Geological Survey, Ottawa, 1919. Pp. 60 (including index), with map, figs. 5.

The area described lies in the district of Timiskaming and includes about 430 square miles. Topographically two elements are recognizable—first, pre-glacial erosion, chiefly of the Cobalt series, which frequently outlines structural features in the pre-Cambrian rocks, and second, drift features, changing with the character of glacial erosion and deposition. The bed rocks are entirely pre-Cambrian, ranging from Keewatin (?) to Keweenawan. The Keewatin (?) rocks are volcanics—extrusives, for the most part, but with small masses of peridotite intrusive into them. The peridotites may prove to be of commercial importance, since asbestos of good quality has been found in them; the rock is highly metamorphosed—kaolinized, or altered to talc, or sericitized. The rhyolites are slightly less quartzose than those of northern Quebec, and the basalts of the Keewatin frequently show pillow structure. All these rocks are highly altered and closely folded and faulted, the folding probably following the deposition of the overlying Kiask series which are dominantly metasedimentaries of many types. From their character, it is thought that the Kiask sediments were laid down rapidly, without much weathering, on an uneven surface.

Kiask sedimentation was succeeded by granitic intrusions and later by a period of basic intrusion, marked by diabase dikes. The overlying Cobalt series is divided into the Gowganda formation (basal conglomerates and very coarse clastics) and the Lorraine quartzite, following Collins. Faulting and some gently folding have been developed here also.

Deposits of asbestos and small deposits of barite, fluorite, and hematite have been found. The asbestos occurs as veinlets in small masses of serpentinized peridotite. The barite, fluorite, and hematite occur in veins. By far the most important mineral however is gold, which has been known in this district since 1917. The gold is closely associated with intrusive granite porphyry; solutions thought to have come from the granite porphyry magma have mineralized the volcanic country rock with the deposition of auriferous pyrite. The gold is in narrow veins of quartz intersecting the granite porphyry or in lenticular ore bodies in the tuff and schist, varying in size up to 75 feet, with their long dimensions parallel to the bedding planes of the tuff and schists.

A geologic map makes the work complete, but the absence upon it of topographic contours is regrettable.

C. H. B., Jr.

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The Lava Field of the Parana Basin, South America. By CHARLES LAWRENCE BAKER.

The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks. V and *VI.* By J. H. L. VOGT.

Origin of the Triassic Trough of Connecticut. By W. G. FOYE.

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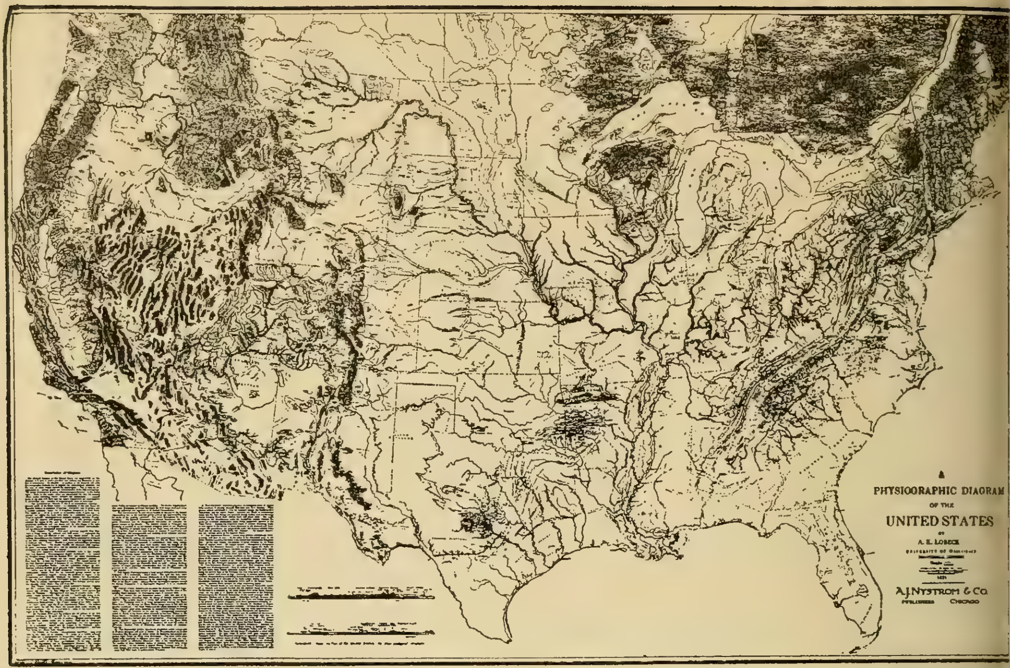
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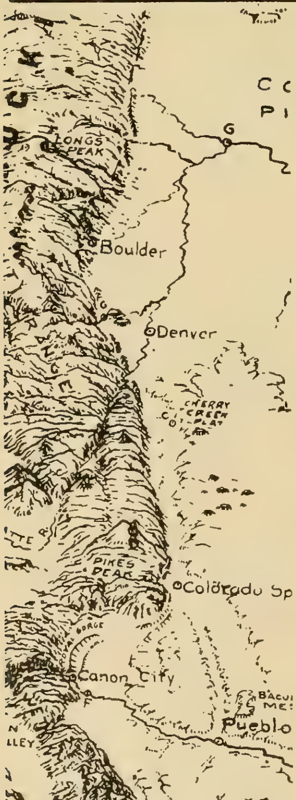
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THE HOT WATER SUPPLY OF THE HOT SPRINGS, ARKANSAS[1]

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CONTENTS

INTRODUCTION

An investigation of the geology of the hot springs in the Hot Springs National Park was recently undertaken for the purpose of determining whether the supply of hot water can be increased. Some new facts were obtained, earlier work critically examined, and recommendations made. The problem is intimately related to the ultimate origin of the water. Thus an investigation begun solely for economic reasons led to a consideration of one of the most

[1] Published by permission of the Director of the United States Geological Survey.

intricate and uncertain realms of geologic theory. Is the hot water of meteoric, juvenile, or mixed origin? On the answer to this question depends, in a measure, the future of Hot Springs, Arkansas.

ACKNOWLEDGMENTS

To the officials of the National Park Service, through whose co-operation the work was undertaken, the writer is indebted for the opportunity of making this study. The local officers of the Park Service and Colonel John R. Fordyce extended numerous courtesies in Hot Springs. Messrs. H. G. Ferguson, O. E. Meinzer, Clyde P. Ross, and W. D. Collins have read the manuscript and offered valuable suggestions. Mr. H. D. Miser has generously allowed the use of much unpublished material from his extensive researches in the geology of Arkansas.

CHARACTER OF THE HOT WATERS

The waters of forty-six springs have been analyzed by Haywood.[1] The mineral contents vary from 170 to 310 parts per million, and in only a few of the springs do the mineral contents fall below 270 parts or rise above 290 parts. Silica is an important constituent ranging from 32.5 to 52.3 parts per million but being usually between 44 and 47 parts. Calcium (Ca) ranges between 26 and 50 parts per million while the bi-carbonate radicle (HCO_3) ranges between 94 and 172 parts per million. The excess of carbon dioxide is satisfied by small amounts of magnesium, potassium, and sodium. The sulphate radicle ranges from 6 to 28 parts per million, and chloride from 2.36 to 3.33. Their salts therefore form only a small part of the total solids. Small quantities of manganese, traces of phosphorus, of combined nitrogen, iron, and aluminum are present. Boron, iodine, and bromium are reported as small quantities or in traces.

The waters of two cold springs which are located at the pavilion north of the Arlington Hotel have a mineral content of 36.4 and 43.7 parts per million. The water is similar to the hot water except

[1] J. K. Haywood, *Report of an Analysis of the Waters of the Hot Springs*, etc. Sen. Doc. 282, 57th Congress, 1st Sess. (1902), pp. 1–78.

for lower mineralization and greater proportionate content of silica and magnesium.

The contrast in mineral content between the hot water and the two cold springs mentioned above seems to be general in the region, and in a later paragraph the available temperature measurements are discussed. In the table below the water of one of the hot springs is compared with four other springs in Garland County. Big Chalybeate, Mountain Valley, Blanco, and Dripping springs are

ANALYSES OF SPRING WATERS IN GARLAND COUNTY, ARKANSAS

(Parts per million)

Constituents	A	B	C	D	E	F	G	H	I	J	K
Silica (SiO_2)	45.6	3.8	16	22	14	12.5	15.1	6.5	5.1	12	15
Iron (Fe)	.2	7.4	.2	.3	1.2	3.4	3.4	.2	.9	4.6	6.3
Aluminum (Al)		......	1.2	.3	Tr.			.1		......	.5
Calcium (Ca)	46.9	70	78	83	76	1.9	3.8	5.3	1.7	3.8	1.4
Magnesium (Mg)	5.1	4.1	12	8.4	2.9	1.4	1.4	.7	......	2.4	1.5
Sodium (Na)	4.7	1.4	6.5	3.9	2.1	2.1	2.2	1.5	.8	.5	2.4
Potassium (K)	1.6	3.1	.5	3.3	.5	.9	1	.3		.1	.9
Bi-carbonate radicle (HCO_3)	168.1	260	284	288	228	12.1	15.1	18	8	2.4	9
Sulphate radicle (SO_4)	7.8	9.4	25	8.2	12	2.5	2.3	1.9	......	21	16
Chloride radicle (Cl)	2.5	2	4.4	7	6.2	1.8	2	2.7	2.9	3.3	4.4
Total solids (calculated)	198.5*	229.7	283	278.7	226.8	42	41	28.3	17.6	49.5	52.4

* Total solids determined.

EXPLANATION OF TABLE

A. Big Iron Spring, No. 15 of Hot Springs group. Small amounts of nitrogenous material; PO_4, .05; BO_2, 1.29; Br and I, trace; Ba and Sr, trace; Li, trace; gases, nitrogen 8.8, oxygen, 3.79, carbon dioxide (free) 6.92, cubic centimeters per liter at 0° C. and 760 mm. pressure. Analyst, J. K. Haywood, 57th Congress, Sen. Doc. No. 282, p. 46.
B. Big Chalybeate Spring; NW. ¼, SE. ¼, Sec. 22, T. 2 S., R. 19 W. Analyst, A. E. Menke. Reported by J. C. Branner, "Mineral Water of Arkansas," *Arkansas Geol. Survey Ann. Rept. 1891*, Vol. I (1892), p. 28.
C. Mountain Valley Spring, Sec. 19, T. 1 S., R. 19 W., 12 miles north of Hot Springs. Reported by Branner, *ibid.*, p. 69.
D. Blanco Spring, NE. ¼, Sec. 1, T. 2 S., R. 21 W. Reported by Branner, *ibid.*, p. 30.
E. Dripping Springs, one of Grandma Chase's springs, 6 miles northeast of Hot Springs. Reported by Branner, *ibid.*, p. 48.
F. Liver Spring. Cold spring in pavilion north of Arlington Hotel. Small amounts of nitrogenous matter; PO_4, trace; BO_2, trace; Br and I, trace; Li, trace; gases, nitrogen 14.36, oxygen 6.24, carbon dioxide (free) 21.8, cubic centimeters per liter at 0° C. and 760 mm. pressure. Analyst, J. K. Haywood, *op. cit.*, p. 75.
G. Kidney Spring. Cold spring in pavilion north of Arlington Hotel. Small amounts of nitrogenous matter; PO_4, BO_2, Br, I, and Li, traces; gases, nitrogen, 15.3, oxygen 5.3, carbon dioxide (free) 28.5. Analyst, J. K. Haywood, *op. cit.*, p. 76.
H. Happy Hollow Spring, 600 yards north of Arlington Hotel. Reported by Branner, *op. cit.*, p. 52.
I. Same as above. Analyst, R. B. Riggs. Reported by Branner, *op. cit.*, p. 53.
J. Red Chalybeate Spring, one of Grandma Chase's springs. NE. ¼, NE. ¼, Sec. 25, T. 2 S., R. 19 W. Reported by Branner, *op. cit.*, p. 50.
K. Happy Hollow Chalybeate, 100 feet west of Happy Hollow Spring. Reported by Branner, *op. cit.*, p. 54.

all relatively strong springs, though none of them are considered to be "hot" springs. The two cold springs in the pavilion, Liver and Kidney, are small seeps and their waters are similar in type and total content with Happy Hollow, Happy Hollow Chalybeate, and Red Chalybeate springs. The last-mentioned spring was not seen but the two Happy Hollow springs and the springs in the pavilion have their origin in the storage of rain water in soil, talus, and the upper fractured part of the underlying rocks. There seems then to be a notable difference between the shallow meteoric waters and the waters of larger springs.

In 1904 Boltwood[1] determined the radioactivity of samples from forty-four springs. He found no evidence of radium salts in the water and attributes the radioactivity to the presence of radium emanation, a gas. The intensity of radioactivity varies from 0.5 to 265.8, a numerical expression for the equivalent uranium represented by the radium emanation ($g \times 10^{-4}$ U). There are, therefore, great differences in the radioactivity of the springs, but their average intensity is 24.9. The cold springs north of the Arlington have activities of 17.4 and 106.8. The spring having an activity of 106.8 is exceeded by only one of the hot springs, and the other has an activity not far from the average of the hot waters. Boltwood says: "As a general summary it can be stated that it has been found impossible to establish any connection between the temperature, flow, location, or chemical composition of the water of the springs and the observed differences in the radioactive properties."[2]

Previous observations on temperature have been reviewed by Weed:

> In 1804 Dunbar and Hunter recorded a temperature of 100° F., for the larger spring and 154° F. for another spring. . . . . The comparison of the old records with those recently made shows that the highest temperature known today is 147° F. as against 154° in 1804, and 150° by Glasgow and 148° by Owen in 1860. In a number of springs there is a decline of 2° since the latter date. Such a slight difference might, however, be due to differences in the manner or place of taking temperatures, or the instruments used in the

[1] Bertram B. Boltwood, *Ann. Rept. Secy. of Interior*, 1904; also *Amer. Jour. of Sci.*, 4th Ser., Vol. XX (1905), pp. 128–32.

[2] *Ibid.*, p. 132.

earlier years may not have been accurate. In one instance, that of Alum Spring, there is a marked decrease in temperature. . . . . In 1804 this had a temperature of 132°. In 1859 . . . . 133° . . . . and today it is but 114.8°.[1]

Haywood[2] gives temperature measurements for forty-four hot springs which range from 95.4° to 147° F. For thirty-nine springs he gives two measurements each, separated by about two months' time. In fourteen of these thirty-nine springs there is a decrease in temperature, in eighteen there is an increase, and in seven there is no change during this interval of about two months. The average difference between readings is 1.5° F. The maximum decrease is 6.3° F. and the maximum increase 6.4° F. With such unsystematic discrepancies in the measurements of a competent observer with good instruments, no conclusion can be reached as to a general decrease in temperature or to the character of the probable variations in temperature.

The Hot Springs are usually considered to be the only hot springs of the region. Three warm springs, however, are known from the vicinity of Caddo Gap, about 50 miles west of Hot Springs. Data concerning these springs collected in 1915 by H. D. Miser are given in the following table:

SPRINGS NEAR CADDO GAP

Name	Location	Geological Formation	Temperature (Degrees Fahrenheit)
Springs in bed of Caddo River at Caddo Gap.....	NE. $\frac{1}{4}$, Sec. 19 T. 4 S., R. 24 W.	Upper part Arkansas novaculite	
North opening........	....	....	94
South opening........	....	....	96.8
Spring on Little Missouri River..................	N. $\frac{1}{2}$, Sec. 17 T. 4 S., R. 27 W.	....	74.3
Spring on Redland Mountain..................	SW. $\frac{1}{4}$, Sec. 12, T. 5 S., R. 26 W.	Arkansas novaculite	77.0

[1] W. H. Weed, "Notes on Certain Hot Springs of the Southern United States," *U.S. Geol. Survey, Water-Supply Paper 145* (1905), pp. 204–5. See p. 439 of this article for references to Weed's authorities.

[2] *Op. cit.*, pp. 30–31.

Certain springs near Hot Springs conform to and others are above the mean annual temperature of the air at Hot Springs which, based on the thirty-year record of the United States Weather Bureau, is 60.5° F. To this temperature the water of "ordinary" springs should closely approximate. Springs above the normal temperature are probably common as shown by the table below:

TEMPERATURE OF GARLAND COUNTY SPRINGS

	Degrees Fahrenheit
Big Chalybeate*	78.9
Grandma Chase's Springs:*	
Dripping Spring	59.2
Red Chalybeate Spring	62.8
Happy Hollow Chalybeate*	64.6
(Not Happy Hollow Spring)	
Potash Sulphur Springs:*	
West Spring	64 –71.6
South Spring	70.2–72
East Spring	68 –69.8
Springs in Pavilion† north of Arlington Hotel:	
Liver Spring	46.4
Kidney Spring	55.4

* J. C. Branner, *op. cit.*, pp. 28, 48, 50, 54, and 77–81.
† J. K. Haywood, *op. cit.*, pp. 75 and 76.

GEOLOGIC SETTING OF THE HOT SPRINGS

Most of the following discussion of the general geology of the region is condensed from a paper by Miser[1] and from the manuscript of a geologic folio by Purdue and Miser,[2] to be published by the United States Geological Survey. The geologic map, Figure 1, is largely a redrawing of the map in this folio. The Hot Springs are situated in that part of Arkansas known as the Ouachita Mountains. These mountains are composed of numerous nearly east to west ridges and several intermontane basins. Some of these mountains are simple ridges, but others are small ranges. The

[1] H. D. Miser, "Llanoria, the Paleozoic Land Area in Louisiana and Eastern Texas," *Amer. Jour. of Sci.*, 5th Ser., Vol. II (1921), pp. 62–89.

[2] Purdue and Miser, "Hot Springs and Vicinity Quadrangle Geol. Atlas of U.S.," *U. S. Geol. Survey*, folio, in preparation.

Hot Springs are located in the southern edge of one of these ranges called the Zigzag Mountains, and on the northern border of a lowland called the Mazern intermontane basin.

The rocks of the Ouachita Mountains are nearly all of sedimentary origin, but at Magnet Cove and Potash Sulphur Springs there are small areas of igneous rocks and at numerous localities near by there are small dikes.

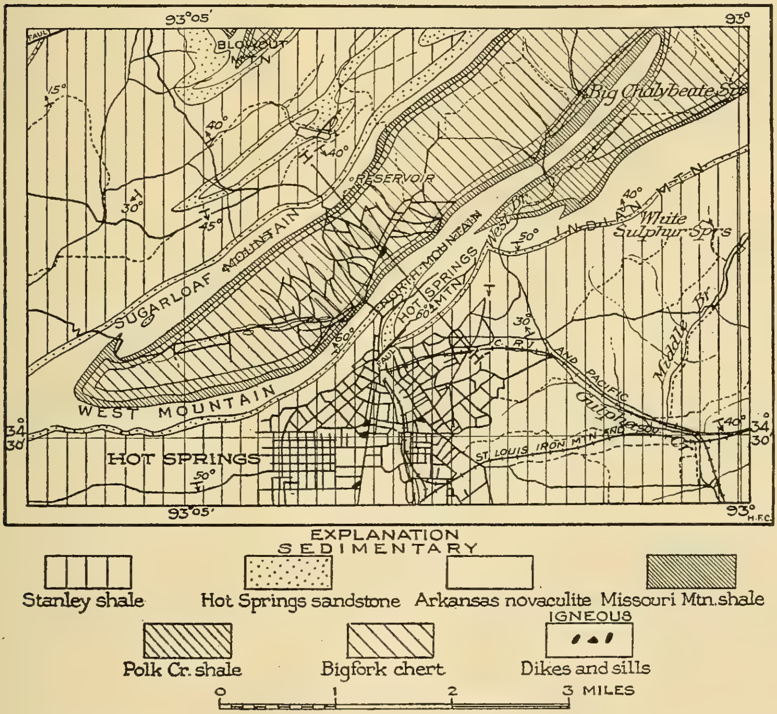

FIG. 1.—Geologic map of vicinity of Hot Springs, Arkansas, after Purdue and Miser.

The sedimentary rocks are indurated and hard, but are only slightly affected by metamorphism. The maximum thickness of the rock beds exposed in the Ouachita Mountains is 37,000 feet, but only a fraction of this total is exposed in the vicinity of the Springs.

The rocks exposed near the Hot Springs consist of the following, though both older and younger are known in the Ouachita Mountains:

GENERAL SECTION OF ROCKS NEAR HOT SPRINGS, ARKANSAS

Geologic Age	Name of Formation and Description	Thickness, Feet
Carboniferous (Mississippian)	Stanley Shale; black, fissile, clay shale, and hard compact sandstone	3,500±
	Hot Springs Sandstone; hard quartzitic laminated gray standstone with heavy bedded conglomerate at the base	200
	Unconformity	
Devonian	Arkansas Novaculite; upper half mainly thin-bedded novaculite and black shale; lower half massive novaculite	500±
	Unconformity(?)	
Silurian	Missouri Mountain Shale; clay shale generally dark greenish drab to black but red in many places	150
	Unconformity(?)	
Ordovician	Polk Creek Shale; black graphitic shale in which graptolites are abundant	200
	Bigfork Chert; thin-bedded gray to black chert much shattered and black shale	700

The rocks mentioned above were deposited one above the other in great sheets. Since their deposition they have been subjected to intense lateral compression which besides lifting the area has produced folds of a general east and west trend. Near the springs these folds have a northeast and southwest trend and the edges of the strata now appear at the surface, and on the map form great looping curves. The major folds consist of numerous smaller folds only a few miles in length, overlapping each other lengthwise. It is with these smaller folds that the springs are associated.

The structures which have the most to do with theories of the origin of the spring waters are the anticlinal fold whose limbs inclose the valley between West, Indian, and Sugarloaf mountains, the synclinal fold of North Mountain, and the anticlinal fold of

Hot Springs Mountain. The character of these folds is brought out in Figures 1 and 2.

GEOLOGY OF THE SPRINGS AREA

The hot water rises in an area of about 20 acres that lies along the east side of Hot Springs Creek, at the southwest base of Hot Springs Mountain. One spring lies west of the creek. Five are said to have risen in the bed, though only one of these can now be found. The spring area is marked by a deposit of calcareous tufa (travertine) from a few inches to eight feet thick over the older rocks. To the tufa the springs are daily making additions, though the present structures for collecting the waters have reduced the rate of formation of the tufa.

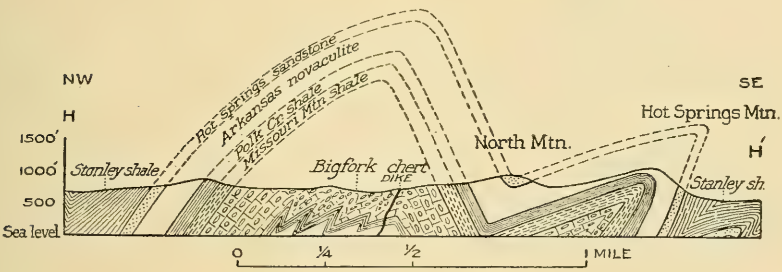

FIG. 2.—Geologic cross-section from Sugarloaf Mountain to Hot Springs Mountain (line *H–H′*, Fig. 1), after Purdue with modifications.

The grounds and springs were carefully mapped by Captain R. R. Stevens, U.S.A., in 1890, and he mapped the tufa, hard-rock outcrops, and springs. Figure 3 reproduces his boundaries for the tufa and for rock outcrops, except that corrections in the rock outcrops have been made at critical points during this investigation. On this map (Fig. 3), the boundaries of the geologic formations have been traced. Landscape gardening, roads, walks, and buildings all tend to conceal outcrops and in a number of places, as stated below, the location of geologic boundaries is uncertain.

The Hot Springs sandstone outcrops on Fountain Street, in Happy Hollow, where it is nearly vertical. From this point it extends along the foot of Hot Springs Mountain southwesterly

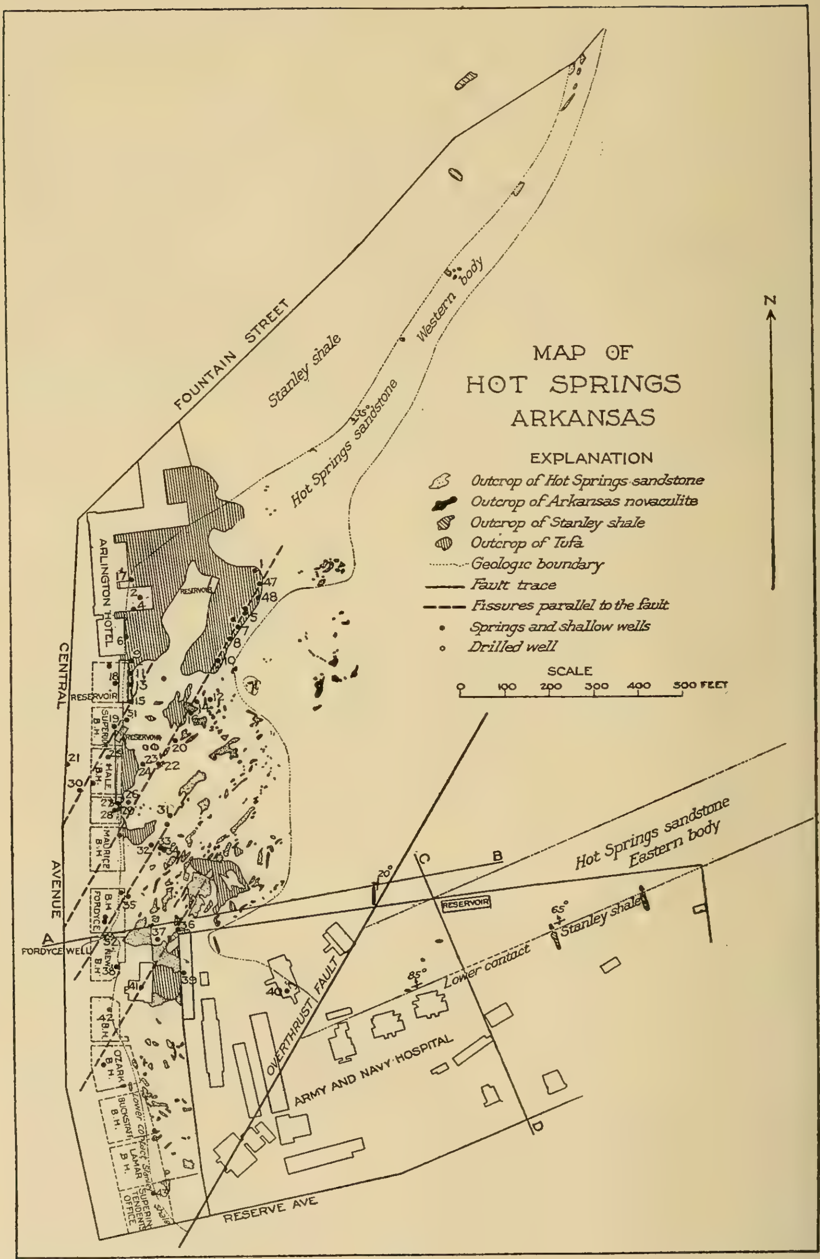

FIG. 3.—Map of the spring area, base and outcrops from Captain R. R. Stevens, U.S.A., 1890.

to the Arlington Hotel and then swings in a broader north and south belt to Reserve Avenue. In this broader belt it has a dip of about 30° and the contact with the overlying Stanley shale is well displayed in the basement of the Maurice, Fordyce, and "new" bathhouses. The lower contact of this body of Hot Springs sandstone extends along the hillside above the springs from the vicinity of the nurses' dormitory in the hospital grounds northwest. In general this contact can be located within 25 feet.

South of Reserve Avenue there are no outcrops of the sandstone, nor are there any in the western part of the hospital grounds.

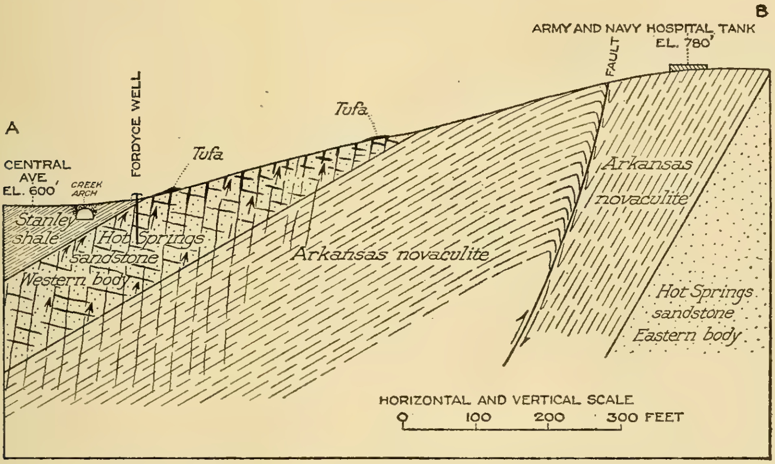

FIG. 4.—Geologic cross-section on line *AB*, Figure 3, through Fordyce well

Since the sandstone is hard and commonly produces outcrops it is assumed that the sandstone does not extend southward any appreciable distance beyond the park line.

This western body of sandstone is the northwestern limb of the Hot Springs Mountain anticline which in its extension along Bathhouse Row forms the nose of the plunging structure. Figure 4 is the cross-section of this part of the mountain on the line *AB* which shows the relation of this body of sandstone to the other rocks.

A second body of Hot Springs sandstone begins on the southeast flank of Hot Springs Mountain and extends southwesterly within the hospital grounds. This eastern body of sandstone dips north-

westerly and is underlain by the younger Stanley shale and overlain by the older Arkansas novaculite. Obviously this body is the overturned southeastern limb of the Hot Springs Mountain anticline. Figure 5 is a cross-section of this part of the mountain and shows the relation of this body of sandstone to the other rocks.

The relation of these two bodies of sandstone once a continuous layer is somewhat uncertain because of the lack of outcrops in the western part of the hospital grounds. If the two bodies are continuous, an extremely close fold is necessary to bend the bed

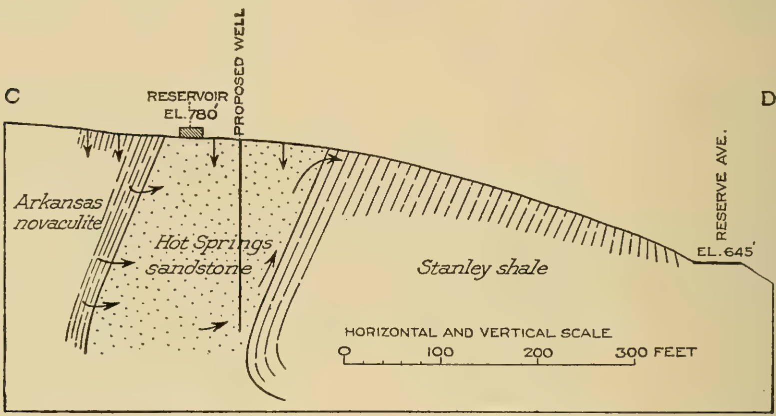

FIG. 5.—Geologic cross-section on line *CD*, Figure 3, through proposed cold-water well.

from a position dipping 30° west at the superintendent's office to 65° northwest near the reservoirs on the hospital grounds, 900 feet away. It seems likely that instead of bending, the beds broke along a thrust fault and this interpretation is shown in Figures 1 and 3. This postulated fault would have a plane which dips to the northwest and a trend about 30° east of north.

RELATION OF THE SPRINGS TO THE WESTERN BODY OF SANDSTONE

As shown in Figure 3, all the hot springs shown on maps since 1890 or now in existence emerge from the outcrop of the western body of sandstone or from the immediately adjacent Stanley shale. Similarly all the bodies of tufa which indicate the position

of springs active or formerly active lie on the sandstone or on the immediately adjacent Stanley shale.

The Hot Springs sandstone of this body is somewhat harder than normal, is a darker color, and is much fractured. These fractures are commonly sealed with quartz and calcite, both apparently deposited by the hot waters. In a number of instances, notably in the Maurice and "new" bathhouses, where excavation has exposed the sandstone, the hot water can be seen emerging from the cracks and fissures of the rock.

The fractured sandstone is then the conduit for the hot water which is prevented from breaking out in the lower depression (the creek bed) by the Stanley shale through which it maintains only a few openings. Similarly the water closes the cracks and joints of the sandstone by deposition and consequently all the springs do not break out at the contact of the sandstone and Stanley shale but many of them emerge higher up the hill.

On the hillside, back of the bathhouses, the outcrops of sandstone are each extended in a northeasterly direction. Each outcrop in addition is marked by strong, nearly vertical jointing in this direction. The maps show also that the spring openings are arranged in lines of which the most marked is that belt of springs from the Egg Spring, No. 1, to the Maurice Bathhouse, which includes the strongest springs of the group. Four such lines of springs are marked on the map. These lines are approximately parallel to the thrust fault, postulated between the east and west bodies of the Hot Springs sandstone. A fifth line may be drawn parallel to the contact of the sandstone with the shale, but this line includes many springs situated on other lines. Obviously, if the sandstone were uniformly permeable and the shale uniformly impermeable, all the springs would lie on the contact.

The strong jointing in the sandstone, and the distribution and elongation of outcrops indicate a fracturing of the sandstone in a direction north northeast parallel to the Hot Springs anticline. Weed[1] noted the line of springs extending from Egg Spring, No. 1, to the Maurice Bathhouse and suggested that this line was a "fault fissure." It seems more likely that this line and the three

[1] *Op. cit.*, p. 201.

other lines of springs simply mark the position of more open joints like the joints visible in the outcrops but that all the joints are parallel to and related in origin to a thrust fault which lies to the south of them. Doubtless similar cracks might have been formed by simple folding. However, the very absence of outcrops in the western part of the hospital grounds seems to be an argument in favor of faulting which would shatter and comminute the rocks along the line of the fault and thus make them more susceptible to erosion. Folding without faulting, on the other hand, would give a a double thickness of sandstone which would be almost sure to outcrop, and this same folding would presumably so shatter the sandstone as to make the line of the fold the locus of springs.

Whatever the ultimate origin of the water, it emerges through the cracks and joints of the Hot Springs sandstone and mainly along the strong jointing parallel to and probably related in origin to the postulated thrust fault. The bearing of these relations on development of the springs is obvious.

THEORIES OF ORIGIN OF THE HOT WATER

In 1804 William Dunbar[1] and Doctor Hunter visited the springs. They observed that the mountain was "principally siliceous, some part of it being of the hardest flint, others a free-stone extremely compact and solid and of various colors. The base of the hill, and for a considerable extent, is composed of a blackish blue shistus, which divides into perpendicular lamina, like blue slate." They make extensive comments on the tufa deposited by the water. They estimated the flow of all the springs at 165 gallons per minute or 237,600 gallons daily. They suggested chemical reactions as the cause of the heat of the water, having found no evidence of volcanic action in the vicinity.

In 1806 a writer relates that he saw a volcanic outburst and streams of molten rock near Hot Springs. He is generally disbelieved by later writers.[2]

[1] Thomas Jefferson, *Message of the President of the U.S. Communicating Discoveries Made in Exploring the Missouri, Red River, and Washita by Captains Lewis and Clark, Doctor Sibley, and Mr. Dunbar*, etc. A. & G. Way, printers, Washington, 1806.

[2] *New York Medical Repository*, Vol. III, No. 1 (1806), pp. 47–50.

In 1860, David Dale Owen,[1] state geologist of Arkansas, published an account of the springs with analyses and observations on temperatures. He rejects all chemical theories of origin of the heat.

On the contrary, I attribute the cause of it to the *internal heat of the earth*, I do not mean to say that the waters come in actual contact with fire, but rather that the waters are completely permeated with highly heated vapors and gases which emanate from sources deeper seated than the water itself.

Owen believed that the novaculite was a sand rock which had been changed by the "permeation" of heated alkaline waters and considered the hot springs merely the dying phase of this extensive movement of water. He gives, however, no mechanism or conduit for these waters.

In 1892 J. C. Branner,[2] state geologist, discusses the origin of the heat and attributes the heat of the water to "coming in contact with the masses of hot rocks, the cool edges of which may or may not be exposed at the surface."

In 1902 Walter Harvey Weed published a geological sketch of the hot springs.[3] Weed noted that the principal springs are arranged along a line running NNE., parallel to the axis of the fold forming Hot Springs Mountain. He thought this a fault fissure. Fissuring in connection with faulting seems confirmed (p. 438). Weed considered that the purity of the waters, particularly their low content of silica, and the included gas which appears to be dissolved air, all point to a meteoric origin of the water, i.e., that the water is derived from rain and differs from ordinary spring water only in being heated. He believed this heat to be derived from still uncooled igneous rock intruded into the sediments below the springs. The upper parts of similar bodies

[1] David Dale Owen, *Second Report of a Geological Reconnaissance of the Middle and Southern Counties of Arkansas*, etc., pp. 18–27, Philadelphia, 1860.

[2] J. C. Branner, "Mineral Waters of Arkansas," *Arkansas Geol. Survey, Ann. Rept., 1891*, Vol. I (1892), pp. 8–23.

[3] J. K. Haywood, *Report of Analysis of the Waters of the Hot Springs*, etc.; and Walter Harvey Weed, *Geological Sketch of Hot Springs, Arkansas.* Senate Doc. 282, 57th Congress, 1st Sess. 1902. Also with modifications *U.S. Geol. Survey, Water-Supply Paper 145* (1905), pp. 189–206, and separate by Interior Department, 1912.

are exposed at Magnet Cove, Potash Sulphur Springs, and as dikes in the vicinity of the Hot Springs.

In 1910, Purdue[1] published an elaborate paper on the origin of the hot water. He follows Weed in believing that the water has a meteoric origin and that in its passage through the ground derives heat from uncooled masses of igneous rock. He goes a step farther and outlines the structural conditions for the collection and transmission of the water. He believes that the water falls as rain in the anticlinal valley between North and Sugarloaf Mountains, where it is absorbed by the Bigfork Chert. "The considerable thickness of this chert, its much fractured nature, and the thin layers of which it is composed all combine to make it a water bearing formation of unusual importance."

The water having been collected in this formation is confined by the impermeable overlying Polk Creek and Missouri Mountain shales. Thus confined the water is conducted beneath the syncline of North Mountain, where it most probably comes in contact with some uncooled mass of igneous rock. Purdue suggests, but rejects the hypothesis that the water is expelled by the cooling of such an igneous mass.

Lindgren,[2] in 1919, accepts Purdue's views and considers that the springs have "clearly derived their saline constituents from the surrounding sedimentary rocks."

Another hypothesis should be advanced. On this hypothesis the water is of deep-seated origin derived from a covered mass of igneous rock intruded into the sediments, but not showing at the surface, which discharges water expelled from its molten interior by the gradual crystallization of its mass, or the water is derived from a deeper less definite but similar mass and rises to the upper crust through a deep, probably fault, fissure. Such water is commonly called juvenile, i.e., new water coming to the surface for the first time.

[1] A. H. Purdue, The Collecting Area of the Waters of the Hot Springs, Hot Springs, Arkansas," *Jour. of Geol.*, Vol. XVIII, No. 3 (1910), pp. 278–85, 3 figs. Also *Indiana Acad. Sci. Proc. 1909*, pp. 269–75, 3 figs. 1910.

[2] Waldemar Lindgren, *Mineral Deposits*, p. 90. New York, 1919.

JUVENILE VS. METEORIC WATER

One of the great triumphs of modern geology has been to establish that the majority of metalliferous ore bodies, including most quartz veins, are deposited by ascending aqueous solutions which are derived from and excluded from crystallizing igneous bodies.

Granite rocks have been traced into pegmatite veins; pegmatite veins into metalliferous quartz veins; metalliferous quartz veins into quartz veins without impurities. It has thus been shown that aqueous vapors and gases gradually cooling and purging themselves of many substances rise through the crust and approach the surface in a purer and purer state. There is no theoretical objection to cold water with a minimum of mineral matter being attributed to a juvenile origin from an underlying crystallizing igneous mass, except the difficulty of proof. The majority of geologists do not hestitate to ascribe ore deposits to deposition from juvenile water, yet they hesitate to ascribe a juvenile origin to water emerging at the surface. It is well then to examine the criteria on which a discrimination between these two classes of water can be based.

Springs of small volume, and large variation in flow and temperature, can usually be referred to a meteoric origin. There are, however, many difficulties in determining the precise geological structure which gives rise to a particular spring. The requisite structures necessary for such a spring are: (1) an intake area, (2) a reservoir, and (3) a conduit to the surface. Under different geologic conditions the three requisites assume a multitude of forms and vary in size according to the hydraulic conditions. In a previous publication[1] twenty-four named varieties, divided into five groups, are described and illustrated. The field geologist, knowing the many possible structures, may have difficulty in deciding on the right one for any particular spring because of lack of evidence. Deep weathering of the rocks and a mat of vegetation and vegetable mold are usual at springs and tend to destroy, locally at least, the

[1] Kirk Bryan, "Classification of Springs," *Jour. of Geol.*, Vol. XXVII (1919), pp. 521–61, 26 figs.

evidence of structure. However, a group of springs of common origin can usually be identified with the geologic structure to which they are due.

Springs of relatively large volume with little variation in flow or temperature present, especially if they are hot springs, difficult problems. Certain hot springs are undoubtedly of meteoric origin and depend for temperature on the descent of meteoric water from the surface into the crust and its rise, without great loss in temperature, to the surface. Such springs are due to the fracture, usually by faulting of the cover of a definite artesian structure, but unfortunately no adequate description of such a spring has yet been published. Buckhorn, Indian, and Willow springs in Antelope Valley, California, which served as examples of the fracture artesian[1] type of spring, are not thermal. Nearby flowing wells, having water of similar chemical composition, are from 200 to 400 feet deep. The artesian circulation in this valley does not go to great enough depths to yield hot water.

Many springs of steady flow and high temperatures arise in localities where it is impossible to postulate a structure which will receive the water at the surface, carry it to depths, and return it to the surface. Waring[2] found that of ninety-eight groups of hot springs in California, thirty-eight rise from granite or granitic rocks; of 155 carbonate springs, some of which are above the normal temperature, thirty-two occur in granite or granitic rocks. In such rocks the hot waters must arise from below through deep fissures. In California there is a notable association of the springs with faults, to which the fissures may be attributed. From these deep fractures in the crust, juvenile water from underlying magmas or incipient magmas may arise or there may be admixtures of meteoric and even connate waters which have or may have a circulation due to obscure or unknown forces. Certainly it seems simpler to assume that the water is juvenile. Certain springs, such as those near the Fish Springs Range, Utah,[3] are associated with faults of large

[1] Kirk Bryan, *op. cit.*, pp. 553–55.

[2] Gerald A. Waring, "Springs of California," *U.S. Geol. Survey, Water-Supply Paper 338* (1915), p. 154.

[3] Kirk Bryan, *op. cit.*, pp. 533–35.

throw and recent age. This association seems a definite indication of juvenile origin. Hot springs in volcanic regions are probably in part of mixed origin. The presence of uncooled or even molten rock near the surface makes easy the heating of meteoric water and its return to the surface. Doubtless some springs in volcanic regions have a wholly meteoric origin, as Hague[1] has proposed for the geysers of the Yellowstone. Yet beneath volcanoes magmas are crystallizing and expelling water. It is inconceivable that all of this water is absorbed in chemical reactions or in the interstices of the rocks below the surface. Some of it, with its contained minerals and gases, must reach the surface.

Springs with steady flow and without great variations in temperature or quantity, especially if they are hot, must then arise from some deep artesian circulation or be of juvenile origin. The artesian circulation should be susceptible of proof on structural grounds. In the absence of such proof the indication of juvenile origin is very strong.

Elaborate investigations of the chemical characteristics of water, with the object of discovering its origin, have so far proved disappointing. Sodium chloride and sodium carbonate waters from granitic rocks carry a strong presumption of juvenile origin since the ordinary springs of such regions have water of the calcium carbonate type.[2] But unusual substances such as boron and fluorine have been found in spring waters of such diverse types as to be without critical value.

ANALYSIS OF THE MERITS OF THE HYPOTHESES

The question of the ultimate origin of the water in the Hot Springs of Arkansas is not only of intense theoretical interest, but has practical bearings. If the water is juvenile there is presumably a constant supply, diminishing very gradually through the centuries in quantity and temperature. When all the water is conserved by adequate structures it is probable that no more can be obtained. If, on the other hand, the water has a meteoric origin, it is variable

[1] Arnold Hague, "Origin of the Thermal Waters in the Yellowstone National Park," *Bull. Geol. Soc.*, Vol. XXII (1911), pp. 101–22.

[2] W. Lindgren, *op. cit.*, p. 64.

in quantity, fluctuating with the seasons or with the groups of years having heavy or light rainfall. Also if the intake area is adequate, heavy drafts on the springs as by pumping should reduce the quantity in the reservoir and increase the absorption of rainfall in the intake area. Such increase in the volume of water flowing through the system may decrease the temperature of the water, an important consideration from the standpoint of use. A meteoric origin implies an intake area and this area must be found and protected from pollution.

It should be confessed that the present state of the science of geology is so imperfect that a definite conclusion as to the ultimate origin of the water in the Hot Springs cannot now be reached. As pointed out by Weed, the absence of unusual substances in the waters, low mineralization, and a gaseous content of oxygen and nitrogen in the proper ratio to form air are facts which do not show any unusual or non-meteoric origin for the water. On the other hand juvenile waters by deposition might purge themselves of all unusual substances, though if they originally contained sodium chloride there are difficulties in accounting for the loss of this stable compound. The radioactivity of the water, or rather the fact that it contains radium emanation (a gas) as determined by Boltwood in 1904,[1] is not of critical significance, for the amount of radioactivity is not unusual in wells and springs.

The previous temperature determinations are analyzed by Weed who rightly considers that they do not indicate either decrease in the heat or fluctuation in heat. Similar conclusions are reached from previous measurements of the water. But the existing measurements of these factors are neither adequate nor systematic. Fluctuations in temperature and volume are easily determinable if they exist. The critical value of such measurements is so great that it is to be hoped that they will be made for a sufficient period to provide adequate data.

The meteoric hypothesis calls for a structure to carry the water from the intake area at the surface to depths and then return it to

[1] Bertram B. Boltwood, "Annual Report of Secretary of Interior, 1904," *Amer. Jour. of Sci.*, 4th Ser., Vol. XX (1905), p. 168.

the surface. As postulated by Purdue,[1] the water falls on the Bigfork Chert in the anticlinal valley between West and Sugarloaf mountains, is absorbed in the chert and passes below the syncline of North Mountain and arises in the anticline of Hot Springs Mountain. The course of the water is shown in Figure 2. The contact of the Bigfork Chert with overlying beds along the southwestern base of Sugarloaf Mountain (see the geologic map, Fig. 1), is about 850 feet above sea-level. Other parts of the chert outcrop as low as 650 feet, this being the elevation at the point nearest the hot springs. The hot springs break out at elevations between 600 and 694 feet. Parts of the intake area are thus at the same level as the springs and below some of them. Assuming the greatest difference 200 feet, it is doubtful if 200 feet of head or 80 pounds of pressure per square inch is sufficient to force the water through the channel assumed by this hypothesis. Even if this head is sufficient, it is remarkable that the water comes across the strike under the North Mountain syncline, when it could swing northeastward and around North Mountain into the Hot Springs anticline without notable change in level. This path is possible because the North Mountain syncline plunges southwestward and near the "Gorge" of West Branch brings the Bigfork chert near the surface. From this analysis it appears that the postulated structure is a very special hypothesis of dubious validity.

Similarly the hypothesis calls for an uncooled mass of igneous rock below the North Mountain syncline to supply heat, for the internal heat of the earth would not raise the temperature the required amount unless the water descended to 5,000 feet and then came to the surface without loss of temperature. Obviously the postulation of such an igneous body is a special hypothesis, particularly when apparently the water could easily avoid the plug by a change in route as shown before. The occurrence of igneous masses in the neighborhood as at Magnet Cove and Potash Sulphur Springs adds probability to this hypothesis, but these intrusions are thought to be of Cretaceous age, a time so remote that it is stretching credulity to believe that rocks of this age are still uncooled at moderate depths.

[1] A. H. Purdue, *op. cit.*

The emergence of the water through the Polk Creek and Missouri Mountain shales into the Hot Springs sandstone requires no special hypothesis, if the thrust fault with associated jointing and fissuring which seem to be indicated by field relations is granted.

By reference to the table of temperatures, page 430, it will be seen that Big Chalybeate Spring has a temperature above normal. In chemical composition the water is of the calcium carbonate type, and of about the same mineralization as the Hot Springs waters, differing mainly in having less silica, (see table, page 427.) It has a strong and according to local observers a steady flow, which measured by H. D. Mitchell[1] was found to be 186 gallons per minute. This spring lies $5\frac{1}{2}$ miles northeast of Hot Springs on the northwestern flank of the mountain which is the extension of the North Mountain syncline. The spring apparently arises from the Polk Creek shale in the flat valley of a tributary of the West Branch of Gulpha Creek. If the water is derived from rainfall on the Bigfork, which saturating the chert arises through a fracture in the shale, it is difficult to account for the abnormal temperature, 18° above the mean annual air temperature, unless an uncooled igneous plug is postulated for this spring also. The contact of the shale with the chert on the west is less than one-tenth of a mile away and less than 20 feet above the spring. The difference in head seems insufficient to force the water to travel to depths and return. On the other hand, southwest of the spring three-fourths of a mile is another anticlinal area of Bigfork chert which has its contact with the shale at elevations between 620 and 820 feet. It might be postulated that water from this area would flow northwest under the syncline and emerge at Big Chalybeate Spring. This hypothesis has the advantage that a depth of 1,000 to 2,000 feet would be attained, and this depth would doubtless be sufficient to account for the temperature of the water. The spring, however, has an elevation between 620 and 640 feet. For this postulate, also, there appears to be a lack of hydraulic head. The origin of Big Chalybeate Spring is then as much an unsolved problem as the origin of the Hot Springs, but because the waters are both thermal

[1] J. C. Branner, *op. cit.*, p. 29.

and similar in chemical composition, it seems likely that they have a common origin. Special hypotheses are invalidated by this probability.

The meteoric hypothesis then suffers from two main defects: (1) A possible lack of head to force the water through the postulated structure; (2) the very special association of uncooled rock with the structure.

The hypothesis of juvenile origin for the waters when examined is perhaps more satisfactory, but suffers from conspicuous defects.

This hypothesis may take two forms: (1) That there is a buried mass of uncooled igneous rock which is discharging water due to cooling and crystallization; (2) that a fracture or fissure extends from the springs into the deep interior of the earth, similar in character to the great fault fractures and through this fracture deep-seated waters, juvenile or of mixed origin, rise to the surface.

A mass of uncooled igneous rock discharging juvenile water is a hypothesis of the same special character as the uncooled body postulated under the meteoric hypothesis. It is no more unreasonable to assume that it is still crystallizing and discharging water, than that it is not crystallizing, but is still hot enough to heat the water by contact. Moreover, the nearby igneous bodies are of Cretaceous age and there is no other evidence of igneous activity in the general region.

That a deep fracture or fissure exists is also a special hypothesis but only special in that it provides that the water rising in this fissure is warm at the surface. A source of heated water is everywhere present in the deeper crust and in regions of disturbance there is a rise in the geotherms and in some instances at least invasion of batholithic bodies. Deep fissures in this general region, though their position is now almost wholly concealed by erosion, must have occurred as late as the Pleistocene epoch during which time the principal uplift is thought to have occurred. Under a hypothesis of recent faulting the position of the springs at the nose of Hot Springs Mountain anticline is purely accidental except that the rising waters have taken advantage of the preexisting fracture by overthrust of the Hot Springs sandstone and the two underlying shales.

Faulting, except in connection with folding, throughout the general region around Hot Springs, is difficult to establish. How ever, in the coastal plain region of central and southern Arkansas and adjacent states, Late Tertiary and post-Tertiary faulting have probably taken place. According to Stephenson,[1] small faults are recognized in connection with the Preston anticline. In the Monroe Gas Field[2] a post-Eocene fault with a total displacement of 150 feet has been mapped. The theory of origin of salt domes advanced by Harris[3] rests on the postulate that faulting on an extensive scale has taken place throughout eastern Texas, Louisiana, and southern Arkansas. Quarternary faulting with a displacement of at least 1,000 feet has been shown for the Jennings oil field.[4] A post-Tertiary fault with a throw of 2 feet to the south was noted by Professor H. A. Wheeler[5] and Colonel John R. Fordyce 3 miles north of Stephens, Arkansas, a town 75 miles south of Hot Springs. This fault appears to be very recent.

The recorded evidence of recent faulting is thus incomplete, but the known uplift of Pleistocene time must have offered favorable conditions for faulting however difficult the matter of proof may be. While no recent faulting has been discovered at or near Hot Springs, the foregoing facts indicate that such faulting is not improbable and may yet be found.

The hypothesis of juvenile origin thus also rests on an insecure foundation since it postulates either a special igneous mass or a special fault fissure. For neither of these is there other evidence.

USE AND DEVELOPMENT OF THE HOT SPRINGS WATER

The quantity of the Hot Springs water used for bathing and drinking fluctuates from year to year but has gradually increased. The

[1] L. W. Stephenson, "Contribution to the Geology of Northeastern Texas and Southern Oklahoma," *U.S. Geol. Survey, Contrib. to General Geol., Prof. Paper 120* (1919), pp. 129 ff.

[2] H. W. Bell and R. A. Cattell, *Louisiana Dept. Conservation, Bull. No.* 7, 1921.

[3] G. D. Harris, *Bull. Louisiana Geol. Survey No. 7* (1908), pp. 75 ff., also *Econ. Geology*, Vol. IV (1909), pp. 12–34, and *U.S. Geol. Survey Bull. 429* (1910), pp. 6–10, Pl. 1.

[4] G. D. Harris, "Oil and Gas in Louisiana," *U.S. Geol. Survey Bull. 429* (1910), pp. 56–61.

[5] Letter, October 22, 1921.

private investment in bathhouses and hotels is large and the government investment in the Free Bathhouse and in the Army and Navy Hospital is considerable. The volume of business can be measured by the number of baths given which reached a maximum of 1,194,872 in 1911. A careful engineering study will doubtless lead to improvements in the present system of distributing the water. Even though economies may increase the capacity of the resort to handle patients and visitors, large future growth of Hot Springs as a health and pleasure resort depends on an increased supply of hot water. The practical means by which additional hot water may be obtained are not here discussed, but it is obvious that development can be attempted intelligently only with accurate knowledge of the origin of the water.

The Fordyce Well, shown on Figures 3 and 4, is 6 inches in diameter and $67\frac{1}{2}$ feet deep. It penetrates the Stanley shale and extends into the Hot Springs sandstone. The well has a flow of hot water amounting to 50,000 gallons daily. Since the well appears not to have decreased the flow of any existing spring or well, it must be supplied with water which had previously reached the surface in minor seeps and concealed springs. Other wells in the same geologic position near the contact between the shale and sandstone will save seepage, but will probably dry up the hillside springs. The resulting concentration of flow will be convenient for a single unified distributing system and the substitution of artificial openings for the natural openings or hot springs will be an inconsiderable sentimental loss.

Whether water not to be considered as salvage can be developed by such shallow wells depends on the ultimate origin and the mechanism of flow of the hot water. Each stage in attempted development of new water will raise anew these fundamental questions.

A DEVONIAN OUTLIER NEAR THE CREST OF THE OZARK UPLIFT

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INTRODUCTION

The Paleozoic history of the Ozark Uplift constitutes an extremely interesting stratigraphic study, and one upon which comparatively little has been written. The earlier stages of this history, up to the close of the Canadian epoch, are fairly well known, for rocks belonging to this and the preceding epochs are well exposed throughout the uplift. Of the later history but little is known, for so thoroughly have the subsequent periods of erosion performed their work, that only small and widely separated outliers of the younger formations remain on the higher parts of the uplift. Around the borders of this dome are belts of younger formations, more or less completely encircling it, and it has always been a question as to how far these formations once extended toward the crest of the structure and which of them, if any, completely covered it. Upon this question no two sets of paleogeographic maps agree. One of the chief reasons for this disagreement is lack of information concerning the region, for, as a whole, there has been little detailed stratigraphic work done in the region of the Ozark Uplift.

In the area around Rolla (110 miles southwest of St. Louis and well toward the crest of the uplift) the existence of outliers of Pennsylvanian and Mississippian age has long been known. The former consist of stratified deposits of sandstone and shale, and cover far greater areas than are shown on existing maps.[1] The Mississippian outliers are, for the most part, small areas covered with fossiliferous, residual bowlders,[2] which have apparently weath-

[1] The new geological map of Missouri, now in press, shows many of the larger Pennsylvanian outliers.

[2] Josiah Bridge, "A Study of the Faunas of the Residual Mississippian of Phelps County (Central Ozark Region), Missouri," *Jour. Geol.*, Vol. XXV (1917), pp. 558–75.

ered out of the basal conglomerates of the Pennsylvanian. In one or two instances, however, there are good reasons for believing that there are small areas of Mississippian rocks which are still in place, and which rest unconformably upon the Jefferson City dolomite (Beekmantown), as do also most of the Pennsylvanian outliers.

A few months ago the junior author discovered a small outlier containing a fauna which is characteristically Middle Devonian in age. This fauna when identified proved to be of sufficient diagnostic value to place the age of the outlier within very narrow

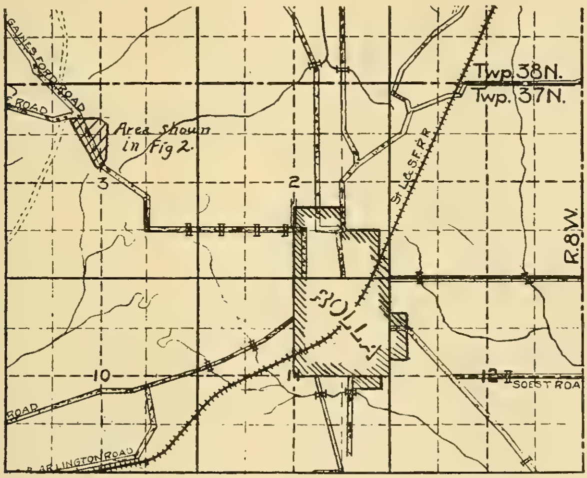

FIG. 1.—Sketch map showing general location of Devonian outlier. The shaded portion represents the area shown in detail in Figure 2.

limits. Inasmuch as Devonian has never before been reported from this area, the finding of this outlier gives a little more light on the history of the uplift, and the purpose of this paper is to describe this occurrence and its fauna, and to add its bit of evidence to the history of the region.

LOCATION AND GENERAL DESCRIPTION

The Devonian outlier lies about $1\frac{1}{2}$ miles northwest of Rolla, in the NE. $\frac{1}{4}$ NW. $\frac{1}{4}$ sec. 3, T. 37 N., R. 8 W. (Fig. 1). It is on the east side of the road and lies fifty feet below the crest of the ridge

(Fig. 2). It occupies a little knoll between two gullies, and when first found consisted of a number of knobs of quartzite projecting from the hill and having a rough alignment. The base was concealed, but just above the top of the outlier were a number of Mississippian bowlders, and on the north, west, and south at higher and lower levels are outcrops of the Jefferson City formation[1] (Fig. 2).

The summit of the ridge is capped by a thin stratum of Pennsylvanian sandstone, and bowlders of Pennsylvanian float are found in abundance at lower levels. The Pennsylvanian rests unconformably upon the Jefferson City formation on the east side of the hill. On the west side there appears to be a thin stratum of Mississippian between them, but the exposures are very poor, and the exact relationships are difficult to determine. The areal distribution of these rocks is shown on the map[2] (Fig. 2).

An excavation was made along the side of these quartzite masses in an attempt to expose the lower contact. This was not entirely successful, but the excavation showed that there was a continuous ledge of quartzite at least thirty feet long and from three to six feet in thickness, increasing in thickness toward the east. Beyond the limits of the excavation there are a few other knobs of quartzite, probably continuous with the part just described. This makes the total length of the outlier about fifty feet, and its greatest width slightly less. It is entirely confined to the little nose between the two gullies, and none has been found on neighboring hillsides. Bedding is indistinct, but there are indications of an eastward dip of about 15°. This is regarded as

[1] The Jefferson City beds exposed on this hillside are among the youngest known in this area. They consist of yellow earthy dolomites (cotton rock) interbedded with chert layers, which are often abundantly fossiliferous, a condition not observed in the lower beds of the same formation in the Rolla area. The fossils consist entirely of one or two species of *Hormotoma,* closely allied to *H. artemesia.* It is quite probable that these upper beds belong to the Cotter formation, which overlies the Jefferson City in the southern portion of the uplift, but which has not been recognized in this area. This cannot be definitely stated, however, until the Cotter and its contained fauna are more completely described.

[2] The writers are greatly indebted to Major C. E. Cooke, professor of topographical engineering in the department of vocational education, and his students, Messrs. Kimball and Hazlewood for making the topographic base for this map.

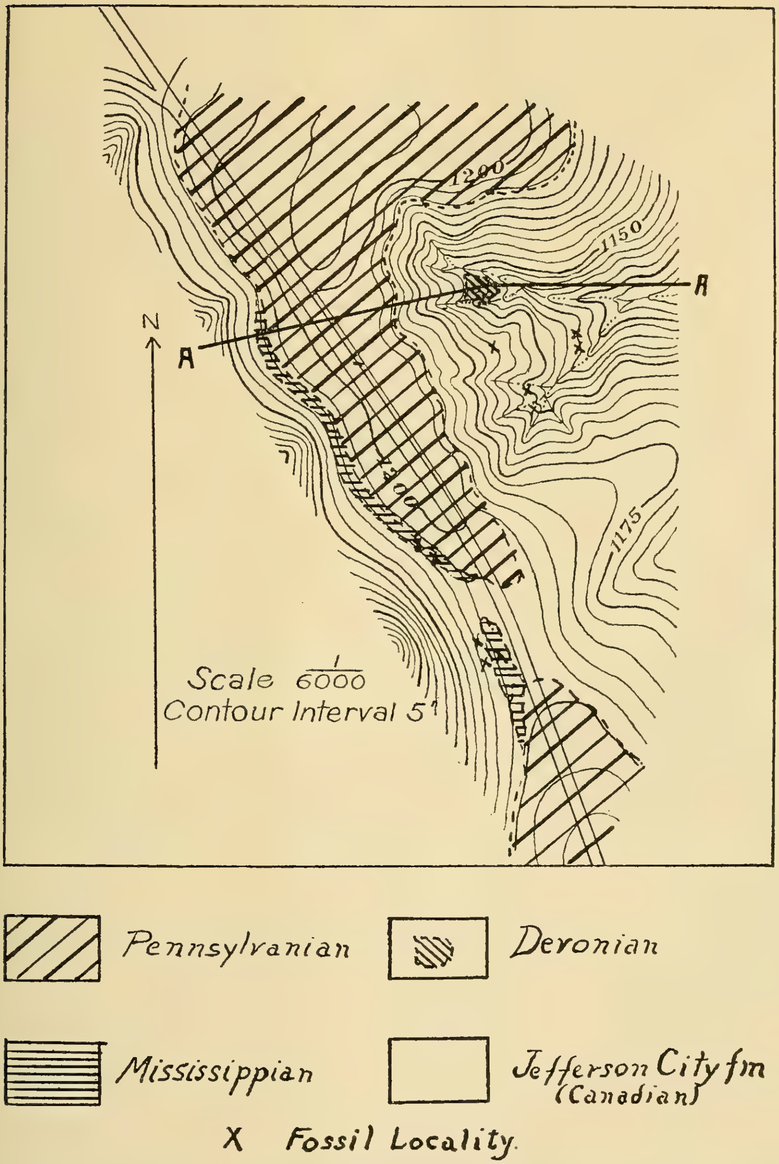

FIG. 2.—Geologic map showing the relationship of the Devonian to the older and younger rocks.

initial dip, and the entire mass appears to rest against an old eastward facing slope developed on the Jefferson City dolomite in a post-Beekmantown pre-Onondaga erosion interval (Fig. 3).

The Jefferson City formation has been found outcropping to within ten feet of the summit of the hill on the east side and to within fifteen or twenty feet of the summit on the west side. Overlying the Jefferson City beds on the west side is a layer of large bowlders containing a typical Burlington fauna. This layer is continuous for several hundred feet, and the bowlders are quite large, and it seems altogether probable that they are in place, or that they have not been moved far from their original location. On the east side of the hill this layer is not as prominent, but bowlders of Mississippian and Pennsylvanian float are abundant all over the hillside, and some of them rest directly upon the Devonian.

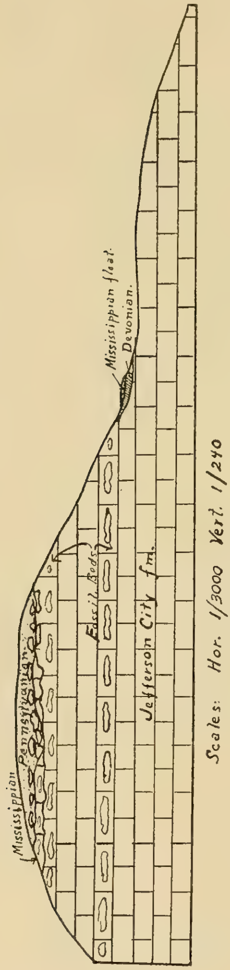

FIG. 3.—Structure section on the line *A–A* of Figure 2

LITHOLOGIC CHARACTERISTICS

Lithologically the Devonian rock is a hard, dense quartzite breaking with a splintery fracture. In color it ranges from white through gray to bluish and almost black. The lighter shades predominate. Thin sections show great numbers of well-rounded quartz nuclei with strong evidences of secondary growth. In some sections the grains show as angular interlocking crystals because of this secondary growth; in other sections, large secondarily enlarged grains are separated from each other by a finely crystalline ground mass of the same material. The rock contains numerous cavities, most of which have been formed by the leaching out of large fossils, and on the surfaces of these cavities are to be found many small but perfect crystals of quartz and of limonite

pseudomorphous after pyrite. The quartzite is somewhat fractured, and these fractures are filled with a soft, yellow, nonfossiliferous, somewhat conglomeratic sandstone.

From the structure and secondary growth it seems evident that the rock was originally a calcareous sandstone, laid down by an advancing sea against an old land mass. The calcareous matter has been completely leached out, and much of it replaced by silica. The soft, yellow sandstone is of later age, either basal Mississippian or Pennsylvanian.

PALEONTOLOGY

Fossils are abundant in the quartzite. They are not evenly distributed, but are most abundant at the base. At first glance, parts of the stratum appear to be barren, but careful search of almost any fragment will reveal fossils. The fossils all occur as external and internal molds, and in most cases the preservation is excellent. Corals and Mollusca dominate the fauna. Other forms are not common, though individuals of a given species may be very abundant.

The following table gives a list of the species which have been obained from this quartzite, and also their occurrence at other localities. Column 1 shows species occurring in the Grand Tower formation in southern Illinois; column 2, species occurring in the Jeffersonville beds at Louisville, Kentucky; column 3, species occurring in Michigan; column 4, species occurring in Ohio; and column 5, species occurring in New York.[1]

[1] Faunal lists:

1. Illinois: S. Weller, "Correlation of the Devonian Faunas in Southern Illinois," *Jour. Geol.*, Vol. V (1897), pp. 625–35.

T. E. Savage, "The Grand Tower (Onondaga) Formation of Illinois and Its Relation to the Jeffersonville Beds of Indiana," *Trans. Ill. Acad. Sci.*, Vol. III (1910).

2. Indiana, Kentucky: E. M. Kindle, "The Devonian Fossils and Stratigraphy of Indiana," *Ind. Dept. of Geol. and Nat. Res., Twenty-fifth Ann. Rept.* (1900), pp. 529–758.

H. Nettleroth, *Kentucky Fossil Shells*. Monograph, Kentucky Geological Survey, 1889.

W. J. Davis, *Kentucky Fossil Corals*. Monograph, Kentucky Geological Survey, 1885.

3. Michigan: C. Rominger, *Geol. Surv. Mich.*, Vol. III, 1876.

4. Ohio: F. B. Meek, *Pal. Ohio*, Vol. I, 1873.

H. A. Nicholson, *ibid.*, Vol. II, 1875.

5. New York: James Hall, *Paleontology of New York*, Vol. IV, 1867, and Vol. V, Part II, 1879.

General: Grabau and Shimer, *North American Index Fossils*, 1910.

TABLE I

List of Species Identified from the Devonian Quartzite at Rolla, Missouri

	1 Illinois	2 Kentucky	3 Michigan	4 Ohio	5 New York
Coelenterata:					
Zaphrentis gigantea, Lesueur	......	x	x	x	x
Zaphrentis prolifica, Billings	......	x	x	x	......
Zaphrentis Sp	......	......	......	......	......
Acervularia rugosa (E. and H.)	x	x	x	......	......
Amplexus yandelli (E. and H.)	x	x	x	......	......
Favosites winchelli, Rominger	......	x	x	......	x
Favosites emmonsi, Rominger	x	x	x	......	......
Favosites basalticus, Goldfuss	......	......	......	x	x
Favosites turbinatus (?) Billings	......	x	x	x	x
Favosites limitaris, Rominger	......	x	x	......	x
Favosites clausus, Rominger	......	x	x	......	x
Cladopora labiosa (Billings)	......	x	x	......	x
Molluscoidea:					
Cystodictya gilberti (?) Meek	x	H*	......	x	......
Stropheodonta demissa (Conrad)	x	x	?	......	x
Rhipidomella vanuxemi, Hall	x	x	x	x	x
Centronella glansfagea, Hall	x	x	x	x	x
Eunella (?) Sp	......	......	......	......	......
Spirifer divaricatus, Hall	......	x	......	x	x
Spirifer grieri (?), Hall	x	x	......	x	x
Martinia maia (?) (Billings)	......	......	......	x	......
Nucleospira concinna, Hall	x	x	......	x	x
Mollusca:					
Actinodesma occidentale (?), Hall	x	x	......	......	......
Conocardium cuneus (Conrad)	x	var.	......	x	x
Conocardium ohioense, Meek	......	x	......	x	......
Bellerophon pelops, Hall	x	x	......	x	x
Bellerophon newberryi, Meek	......	......	......	x	?
Hormotoma maia, Hall	......	......	......	......	......
Igoceras conicum (Hall)	x	x	......	x	x
Loxonema robustum (?), Hall	......	......	......	x	......
Cyclonema crenulata, Meek	......	x	......	x	......
Callonema bellatula, Hall	......	x	x	x	......
Callonema humile, Meek	......	x	......	x	......
Callonema conus, Kindle	......	x	......	......	......
Tentaculites scalariformis, Hall	x	x	......	x	x
Coleolus tenuicinctum, Hall	x	......	......	H	H
Orthoceras Sp	......	......	......	......	......
Gomphoceras Sp (2)	......	......	......	......	......
Zittleoceras nereus, Hall	......	......	......	......	x
Arthropoda:					
Phacops cristata, Hall	x	x	......	......	x
Proetus clarus, Hall	x	x	......	......	......
Dalmanites calypso, Hall	x	x	......	x	x

*H indicates that species occurs in the Hamilton at that particular locality.

CORRELATION

From the foregoing table it is evident that this fauna is of Onondaga age, and that it is the partial equivalent of the Grand Tower formation of southern Illinois and southeastern Missouri. Its affinities are entirely with the eastern Devonian and have no resemblance to the later Devonian faunas of Iowa and north central Missouri. Of the thirty-seven identified forms, seventeen occur in the Grand Tower formation of southern Illinois, thirty in the Jeffersonville beds of southern Indiana, thirteen in the Onondaga group of Michigan, twenty-two in the Onondaga of Ohio and eighteen in the Onondaga of New York. These figures are not exact and are probably too low, for the faunal lists from the various regions are incomplete and represent compilations in most cases. The most complete lists are those from the Grand Tower formation and from the Jeffersonville beds. Weller[1] and Savage[2] have shown the relationship of the Grand Tower fauna to the Onondaga of the eastern United States.

Savage[3] has also shown that the Jeffersonville beds are the equivalent of the upper portion of the Grand Tower of Illinois. Since more than 80 per cent of the forms occurring at Rolla are also found in the Jeffersonville beds, it seems certain that this outlier belongs to the upper portion of the Grand Tower formation. In Ste. Genevieve County, Missouri, Weller[4] assigns over two hundred feet of strata to the Grand Tower formation. Certain horizons in this formation are reported to be full of corals, but until the faunal lists for this formation are completed, a closer correlation cannot be made.

CONCLUSIONS

The presence of a Grand Tower outlier at Rolla indicates a much greater submergence of the Ozark uplift during Onondaga time than has commonly been supposed. The nearest outcrops of the Grand Tower formation are at least 100 miles to the east. The

[1] S. Weller, *loc. cit.*

[2] T. E. Savage, *loc. cit.* [3] *Ibid.*

[4] Stuart Weller, unpublished manuscript on Ste. Genevieve County, Missouri, Missouri Bureau of Geology and Mines.

St. Francois Mountains, the structural center of the uplift, are directly between the two exposures, and it is not believed that these were covered in Devonian time. In view of the thinning out of the Devonian to the north, it may be assumed that the Onondaga sea extended westward along the southern border of the St. Francois Mountains, and that it may have covered much of the southern portion of the uplift. Further field work may reveal other outliers, which will enable the boundaries of this sea to be traced more definitely.

THE EARLY PRE-CAMBRIAN FORMATIONS OF NORTHERN ONTARIO AND NORTHERN MANITOBA

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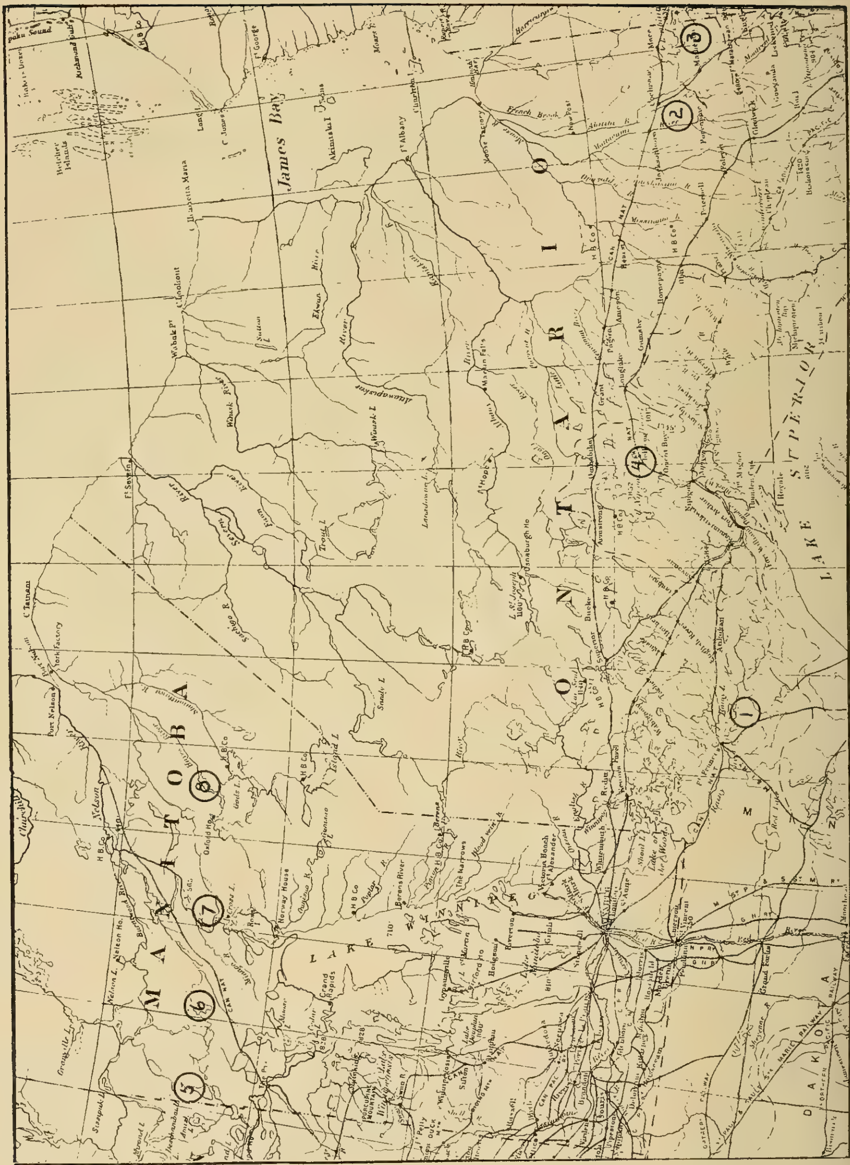
The classification of rocks earlier than the Cambrian is one of the difficult problems of geology. Correlation from point to point rests largely upon lithology and upon the succession of lithological units, and difficulties arise both from original similarity of formations of quite different age, and from similarity through the developments of the same metamorphic minerals in rocks originally of quite different character. Correlation is especially difficult in formations of early pre-Cambrian time, since these have undergone much longer periods of deformation than have the later ones. Varying successions of these early rocks have been worked out in some detail in different parts of the Canadian shield, and many attempts have been made to formulate a generalized succession that will fit all areas. None of these attempts has been successful, since the determination of the age of a formation by its likeness to a certain formation as described in an accepted classification, is liable to lead to quite erroneous conclusions. A review of some areas in western Ontario and northern Manitoba will show the diversity in various sections and will, it is believed, make possible certain generalizations.

RAINY LAKE DISTRICT

The first attempt to subdivide the early complex was made by Lawson[1] in the Rainy River district. He recognized two formations earlier than the first granite intrusion. The lower of these is his *Coutchiching series*, which he believes to be the oldest formation in the area. The Coutchiching rocks consist of mica

[1] *Geol. Survey of Canada, Ann. Rept.*, New Series, Vol. III, Part I (1887–88).



DISTRICTS

Rainy Lake	1
Porcupine	2
Abitibi	3
Lake Nipigon	4
NW. Manitoba	5
Wekusko L.	6
Cross Lake	7
Knee Lake	8

Fig. 1

schists, garnetiferous mica schists, hornblende schists, and phyllite.[1] In some of the mica schist, quartz makes up three-fifths of the rock mass, biotite one-fifth, with zoisite the other important mineral present. It seems evident from Lawson's descriptions of the field occurrences and from the results of petrographical examinations and chemical analyses as given in his report, that the rocks are sediments, possibly of somewhat abnormal types. They are entirely clastic; no limestones have been found in association with them. A striking and peculiar circumstance is the lack of coarse sediments or conglomeratic beds in this supposedly thick series. It seems possible that these rocks were formed along the seaward margin of a delta which supplied large quantities of fairly fine débris, the site of deposition for the Coutchiching being so far from shore that no gravels were supplied, but not far enough out to allow the formation of limestones, assuming that conditions were suitable for the deposition of lime rocks at that early period.

The *Keewatin series* consists of: "(1) fine-grained greenstones showing frequently ellipsoidal or amygdaloidal structures or both; (2) coarser-textured greenstones showing neither ellipsoidal nor amygdaloidal structures; (3) greenstone schists of varying degrees of schistosity; (4) rather massive chlorite schists; (5) evenly fissile chlorite schists; (6) irregularly cleaved chlorite schists; (7) black glistening hornblende schists usually on the periphery of the Keewatin belts where they come in contact with granitic intrusions; (8) gray felsite sometimes amygdaloidal; (9) sericitic schists; (10) various stratified grayish-green schists, probably ash beds; (11) agglomerates; (12) gray siliceous slates and schist; (13) banded cherts; (14) mica schists; (15) limestone."[2]

This group is clearly made up for the most part of lava flows and their derivatives with minor amounts of sediments interbanded with the igneous rocks. In summary, then, it may be said that the Coutchiching consists chiefly of sediments, with possibly some beds, such as the hornblende schists, of igneous origin; the Keewatin series is chiefly igneous, with minor sedimentary beds intercalated with the lava flows. There seems

[1] Lawson, *Memoir 40, Geol. Survey of Canada*, p. 28.

[2] *Ibid.*, p. 35.

to have been no erosion period between the formation of the two series.

Lawson considered the Coutchiching to be a distinct series underneath the Keewatin, but the international committee to revise the classification of pre-Cambrian formations did not agree. In some of the areas examined rocks mapped as Coutchiching in the original work were found to belong to the Seine series, which lies with a great unconformity above the Keewatin. Mistakes of this kind are quite to be expected in determining somewhat similar series under the difficult conditions of the original mapping. Lawson, in his later publication, *Memoir 40, Geological Survey of Canada*, admits these mistakes, but still maintains that there is a great sedimentary series below the Keewatin. Some competent observers who have visited the area agree with him.[1] The point has also been raised that the Coutchiching may not be the oldest formation, but may be similar to the interbedded sediments—(12) in the Keewatin—and that beneath the Coutchiching again there may be still older lava flows. If so, it is argued, the Coutchiching series may quite logically be included as part of the Keewatin.

PORCUPINE DISTRICT

The earliest rocks in the Porcupine district of northern Ontario consist of pillow lavas with schists derived from them, "carbonate" rocks of doubtful origin, iron formation, and some fragmental rocks of doubtful character.[2] A group of undoubtedly sedimentary rocks is correlated by Burrows with the Temiskaming series. They consist of "conglomerate, interbanded slate and greywacké, and quartzite." The relations of these sediments to the Keewatin group are shown by the following quotations:

> A contact of the sedimentary rocks with the volcanic rocks can be seen immediately south of the open pit at the Dome mine. Fragments of the volcanic series are abundant in the sedimentary series, and it is likely that the conglomerate has been deposited on the surface of the volcanic series of the Keewatin. . . . . However, one half a mile north west of the north end of

[1] Private Communications, F. J. Alcock and T. L. Tanton.

[2] A. G. Burrows, "The Porcupine Gold Area," *Third Ann. Rept. Ont. Bureau of Mines*, Vol. XXIV, Part III (1915).

Porcupine lake in lot 11 in the fourth concession of Whitney there is a contact of the sedimentary series with pillow lava in which the relationship suggests an igneous contact, that is that the pillow lava is later than the sedimentary rock. It is therefore probable that some of the pillow lavas mapped with the Keewatin are later in age than the Temiskaming series.

While there is much evidence pointing to a separate sedimentary series of rocks the possibility of some of what has been called Keewatin being contemporaneous with the Temiskaming or of some of the sediments being of Grenville age must be considered. Toward the southwest from the open pit at the Dome mine there is a narrow band of conglomerate which has been mapped at Temiskaming. Much of the material in this band immediately north of the readily recognized pillow lava and amygdaloidal rock resembles volcanic fragmental or agglomerate. There is no break, however, between the apparent volcanic fragmental and the interbedded slate and greywacke which occur along the south margin of the open pit and which can be followed northward for a mile. If the rock above mentioned is a volcanic fragmental, and not a true conglomerate deposited on an eroded surface, then there is reason for considering the pillow lavas, fragmental rocks, slates, greywacké and conglomerate as belonging to one series. For lithological reasons it seems preferable to consider the large area of sediments as a separate series.

It is apparent that Burrows recognized the possibility of an interbedded series of sediments and volcanics, but that he decided to correlate the sedimentary part of the series with the lithologically similar Temiskaming rather than accept an alternative hypothesis of a great continuous series made up of lava flows, volcanic fragmentals, and true sediments. The evidence for an erosional unconformity between the volcanics and sediments does not seem to be conclusive.

ABITIBI DISTRICT

The district south of Lake Abitibi has recently received considerable attention, and an interesting series of rocks has been found.[1] Lava flows which are classed as Keewatin are exceptionally well developed, and the scoriaceous surfaces of successive flows make it possible to determine the top and bottom of the formations. Sediments are associated with these lavas. The following is a quotation from the report mentioned:

[1] C. W. Knight, A. G. Burrows, P. E. Hopkins, and A. L. Parsons, "Abitibi Night Hawk Gold Area," *Eighteenth Ann. Rept. Ont. Bureau of Mines*, Part II (1919).

In our map sheet there is an interesting series comprised of highly altered sediments which are closely associated with the Keewatin. . . . . One belt has an apparent thickness of one and one half miles and a length of 11 miles. . . . .

The rocks in the three large areas mentioned in the preceding paragraph consist of slate, greywacké, quartzite, and a little conglomerate, all of which have been altered to schists. Both the cleavage and bedding of the sediments have nearly vertical dips, but there are usually small angles between their strikes. A little chert is also present. Conglomerate schist was seen in four localities and, in each case, near the outer edge of the sediments. . . . . The pebbles which are somewhat flattened, consist of quartz porphyry and greenstones, suggesting an unconformity between the sediments, on the one hand, and the greenstones and quartz porphyry on the other. However, the only good contacts which were seen between the sediments and the greenstones were on lot 7 in the second concession of Coulson township and these might suggest that the sediments were interbedded with the pillow lavas of the Keewatin. It may be added that in this locality the banded cherts which appear to be a part of the main group of sediments are older than the pillow lavas. In view of these apparently conflicting observations it is seen that the relationship between the Keewatin lavas and these old sedimentary rocks has not been definitely worked out. Possibly the conglomerates may be of interformational origin or may belong to the Temiskaming series.

It seems clear that there are two possibilities. Either the lava flows here called Keewatin are in reality much younger than those usually classed as Keewatin, younger in fact than the Temiskaming series, or there is a great interbanded series of lava flows, tuffs, and sediments. The presence of conglomerate in such a series is quite to be expected.

LAKE NIPIGON DISTRICT

In the Kowkash area east of Lake Nipigon, Hopkins[1] has found a series of rocks which he calls the Marshall Lake series. This group consists of quartz-mica schists, garnet, and staurolite schists. Hopkins says:

The chemical composition, microscopic evidence, and frequent occurrence of alternating coarse and fine bands in these quartzose rocks suggest that they are clastics or volcanic fragmental rocks deposited in water. Since they are interbanded with ellipsoidal lavas on Cross lake and contain some iron formation they are apparently closely associated with the Keewatin.

[1] *Ann. Rept. Ont. Bureau of Mines*, Vol. XXVI (1917), p. 206.

No evidence is given for considering these rocks as volcanic fragmental types, and judging from the description they seem to be normal fine-grained clastic sediments.

Along the Canadian Northern Railway east of Lake Nipigon,[1] Burrows found a complex of igneous and clastic rocks, all of which he grouped tentatively as Keewatin. Concerning them he says:

> The age relationship between the mica and quartzose schists of sedimentary origin and the pillow lavas and other igneous rocks is not known. For the most part the sedimentary rocks stand so nearly in a vertical attitude that their relationship cannot be determined. It seems advisable to group all these rocks with the Keewatin until information is available to show that the sedimentary rocks may possibly be older than the lavas.[2]

Both Burrows and Hopkins classify certain other conglomerate rocks as Temiskamian, but in neither area are the conglomerates found definitely unconformable with the lavas. The correlation is a lithological one in both cases, the later age being assumed from the presence of pebbles of jasper, greenstone, and granite in the conglomerate beds.

PRE-CAMBRIAN SECTIONS IN MANITOBA

Various sections in northern Manitoba have been examined in some detail, and a strip of country extending almost across the province has been mapped. Beginning at the Saskatchewan boundary, where the pre-Cambrian basement emerges from beneath the Paleozoics, a series of three map sheets extends eastward to the Hudson's Bay Railway. Northeast of Lake Winnipeg two areas—the Cross Lake district and the Knee-Oxford Lake district—have been studied.

In the most westerly section the oldest rocks are ellipsoidal greenstone and derived schists.[3] Supposedly later than these is a thick series known as the Kisseynew gneiss, a garnetiferous, quartz-biotite gneiss apparently sedimentary in origin. There is also a group of slates, quartzites, and conglomerates. The latter are quite evidently the result of torrential deposition probably in

[1] *Ann. Rept. Ont. Bureau of Mines*, Vol. XXVI (1917), p. 232.

[2] *Ibid.*, p. 239.

[3] *Mem. 105, Geol. Survey of Canada.*

river flood plains. This group, the lower and upper Missi formations, are, however, on structural evidence, thought to be separated by a mountain-making and erosional interval from the volcanic rocks and are therefore not considered in this discussion of the early pre-Cambrian formations.

In the Wekusko (Herb) Lake district, approximately seventy-five miles east of the Saskatchewan-Manitoba boundary, ellipsoidal lavas occur which are apparently the continuation, so far as lavas can be continuous, of the area just described. They are lithologically similar and outcrop practically continuously across the interval. Quartz-biotite gneisses lithologically similar to the Kisseynew gneiss are associated with them. Staurolite schist, conglomerate, slate, and acid volcanic flows also occur. All these are interbanded with the basic ellipsoidal flows.

Alcock's summary[1] is very definite with regard to the relations and character of these early rocks:

> The pre-granite complex is interpreted, therefore, as representing a series of interbanded sediments and volcanic rocks of varying composition. Though the sedimentary division contains members which have pebbles of granite, quartz, and volcanic rocks, no evidence was found that these pebbles were derived from any rocks now exposed in the area, nor was any evidence found, aside from the presence of these bowlders and pebbles, which would suggest that the members containing these fragments represent a younger series infolded with the complex and separated from it by an erosional unconformity. The whole group is regarded as a series of flows and contemporaneous sediments. The absence of limestone, the dominance of clastic sediments, the irregularity of the beds, the great thicknesses locally, the recurrence of conglomeratic horizons, point to a continental rather than to a marine origin for the series.[2]

At Cross Lake, an expansion of the Nelson River below Lake Winnipeg, a series of sedimentary rocks consists of para-gneiss, arkose, and conglomerate; some of the gneisses are garnetiferous. Greenstone, which in places is ellipsoidal, occurs in the area. The sediments are interbanded with the lavas. They are interpreted as continental, probably fluviatile deposits.[3]

[1] F. J. Alcock, *Memoir 119, Geol. Survey of Canada.*

[2] *Ibid.*, p. 24.

[3] F. J. Alcock, *Summary Report, Geol. Survey of Canada*, Part D (1919).

Eastward across the divide on the headwaters of the Hayes River, early pre-Cambrian rocks are exposed at Knee Lake and Oxford Lake.[1] A lower, dominantly sedimentary part, consists of rusty weathering garnetiferous biotite gneiss, impure quartzite, slate, conglomerate, tuffaceous rocks, and some interbedded flows. The thickness is probably several thousand feet. Above the dominantly sedimentary group are flows of ellipsoidal weathering lavas together with a few bands of iron formation. These groups are apparently merely parts of a great continuous series. The sediments are in great part typical continental deposits.

COMPARISON OF THE FORMATIONS

From the descriptions of the various areas quoted it is clear that there are two distinct types of rocks in the early formations: (1) volcanic flows now altered to greenstone and chlorite schist, and (2) sedimentary rocks consisting largely of gneiss but also in places including slate, quartzite, and minor amounts of conglomerate. The gneisses retain evidences of bedding although in many occurrences metamorphism has destroyed some of the original texture. Analyses of specimens of these old gneisses are comparable to analyses of typical sediments. The slates commonly show the original bedding as color variations at slight angles to the fissility. Some arkosic rocks still retain the cross bedding and ripple-markings of the original sands and conglomerate, even though the matrix may be thoroughly schistose, with complete recrystallization of the constituent minerals, and are still recognizable as water-laid clastic rocks.

The peculiarities of all the sedimentary formations of this early period are the comparatively small amount of conglomerate and the complete lack of limestone. The sediments found in Manitoba are continental deposits probably formed under deltaic or piedmont conditions. The lack of any large amount of coarse material is evidence that no high land masses existed near the site of deposition, but the ripple-marking and cross-bedding of some of the rocks indicate shallow-water conditions during the formation of some of the beds. The early sediments in other areas

[1] E. L. Bruce, *Summary Report, Geol. Survey of Canada*, Part D (1919).

are similar to those in Manitoba, and it may be assumed that they were formed in much the same way.

The volcanic rocks are lithologically similar throughout the whole region discussed, and this striking similarity quite naturally has led to the correlation of these rocks wherever they occur. The flows are ellipsoidal or massive greenstone of medium basicity. Many of them are now altered to schists. Along with these, minor thicknesses of acidic flows and tuffaceous beds occur. In many districts thin sedimentary beds are found with the igneous rocks. Banded iron formation is very commonly associated with the flows of basic composition.

Although the rock types are comparable, the age relations are variable. In some districts the sedimentary rocks lie above the volcanics. In others the two are interbanded, and in others the greater thickness lies below the igneous rocks. No erosion interval has been recognized; the separation into igneous and sedimentary divisions made in some localities, is purely arbitrary, and implies simply that the divisions are dominantly clastic or dominantly igneous. For in most occurrences there are sedimentary beds among the igneous rocks and flows intercalated with the sediments.

CLASSIFICATION

None of the general classifications of pre-Cambrian formations is applicable to this early complex. The classification[1] accepted by the International Committee places the Keewatin as the lowest formation and does not recognize the presence of great thicknesses of clastic sediments below the great unconformity at the base of the Huronian, nor Lawson's Coutchiching as a great series below the igneous flows. There are, however, not only in the Rainy River district, but in other districts, thick sedimentary formations below the oldest lava flows recognized in those districts. It is possible, as suggested, that other older lava flows exist beneath the sediments, but if so, the application of the term Keewatin, if it is to be retained, must be extended to include a large amount of sedimentary rocks.

[1] *Jour. of Geol.*, Vol. XIII (1905), pp. 89–104.

On the other hand, the original classification suggested by Lawson, in which the sedimentary Coutchiching is the oldest formation, cannot be applied to those successions in which the sediments are interbanded with lava flows or even lie above rocks which are lithologically similar to the Keewatin.

From theoretical considerations it seems unlikely that any of these formations can be used to correlate successions in different districts. Commonly the basic flows have been used in this way. Since they are lavas, it is impossible that any one eruption could have extended to any great distance, and hence correlation on the basis of lithology of separate flows must be most uncertain. Nor is this affected by the possibility that many of the flows are subaqueous, as there is no evidence that the bodies of water beneath which the flows may have been extruded were large or continuous. In fact, in some instances the interbedding of ellipsoidal flows and shallow water or terrestrial sediments is evidence that the bodies of water were limited in area and of brief duration. Correlation by means of the sedimentary beds is even less reliable. The conglomerate, slate, and gneiss of this early period are believed to be almost entirely of terrestrial or shallow-water origin. No bed formed in this way could be expected to have great lateral extent, and no determination of age can be made on the ground of its similarity to rocks in other districts.

Since no erosion break has been recognized in any of the successions yet worked out, and since there is this very marked difference in the relations of sedimentary and igneous rocks in various areas, it is plain that no course is possible, at present, except the interpretation of the early part of the pre-Cambrian as a period of volcanic activity in which eruptions of lava alternated with deposition of ordinary clastic sediments. These periods of eruption were recurrent, but not necessarily contemporaneous even in neighboring districts. Hence the succession of volcanic and sedimentary rocks is naturally not the same in any two districts. The result is a great thickness of lavas, tuffs, and sediments, all of which belong to one great period in the earth's history. It is manifestly impossible to apply to rocks of such origin either of the terms Keewatin or Coutchiching and, if the view set forth here be

accepted, it seems necessary to restrict those terms to the original area in which they were applied. If it seems convenient in any other area to divide the rocks of this early period, local names should be applied to the divisions without implying any wide regional correlation. Detailed examination may later make clear the time relations of events; and if so, correlations can then be made. If that ever becomes possible, it seems more than likely that instead of rocks of similar lithology being found to belong to the same period, it will be found that flows in some districts are contemporaneous with sediments in others, or that a period of deposition of sediments in one section corresponds to a period of local erosion in a neighboring section.

Although at present sufficient work has not been done to make correlation possible, it is interesting to note the distribution of the sediments in relation to the igneous rocks. In western Manitoba the sediments lie above the flows. In north central Manitoba flows and sediments are interbedded. In eastern Manitoba and western Ontario the great mass of sediments lies beneath the volcanics. In eastern Ontario the two are again interbedded. These relations can be explained by the presence of a great area of continental deposition extending southward from an old land mass in central Canada in the very earliest times. Over this area, terrestrial and shallow-water deposits were laid down on river plains, piedmont fans, or deltas along whose margin sediments were interbedded with subaqueous lava flows. Still farther out no sediments at all were deposited until a later readjustment of land and water shifted the zone of sedimentation to areas where, previously, only igneous rocks were forming. At the same time the central area became the site of igneous activity and the extrusion of lavas over the clastic sediments already laid down. At present this can be considered only a suggestion resting upon slight field evidence.

SUMMARY

The points raised in the preceding discussion can be settled only by more detailed work, but the following conclusions seem to be warranted from present knowledge:

1. In the early part of the pre-Cambrian, periods of volcanic activity alternated with periods of normal sedimentation. The resulting rocks form one great series.

2. At present local terms only should be used in subdividing this complex. The terms now in use in the generalized classifications are inapplicable, and should be restricted to the areas in which they were used originally.

3. The sedimentary record of the early pre-Cambrian seems to be largely one of continental rather than marine conditions. Some of the deposits were undoubtedly deltaic, others were likely piedmont, lacustrine, fluviatile, and even basin deposits. It points to the conclusion that even from the very earliest pre-Cambrian, the Canadian shield was a positive element.

THE TIME OF GLACIAL LOESS ACCUMULATION IN ITS RELATION TO THE CLIMATIC IMPLICATIONS OF THE GREAT LOESS DEPOSITS: DID THEY CHIEFLY ACCUMULATE DURING GLACIAL RETREAT?

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Although deposits similar in several respects to glacial loess are forming today near the borders of certain deserts and along the bluffs of some great rivers, the widespread, thick loess deposits which are associated with some drift sheets imply peculiar climatic conditions, for no deserts are now close to these ancient deposits, and parts of them are far from great rivers. There have been many discussions of the probable origin of loess, and thus, indirectly, of its climatic implications. Much has been learned, among other things that different deposits accumulated under different conditions. But one question appears not to have been satisfactorily settled, that is, At what time, in respect to glaciation, did the greater part of the accumulation take place? Several American and European students have thought that the great loess deposits date from interglacial times. On the other hand, Penck has concluded that the loess was formed shortly before the commencement of the glacial epochs; while many American geologists have held that most of the loess accumulated while the ice sheets were at approximately their maximum size. Chamberlin and Salisbury,[1] McGee, and others lean toward this view.

There is evidence in support of each of these hypotheses, but it seems well to reconsider the possibilities that a large share of the great deposits associated with glaciation were formed at the one other possible glacial time, namely immediately following the retreat of the ice. Recent evidence affords light not available to the workers

[1]Chamberlin and Salisbury, *Geology*, Vol. III (1906), pp. 405–12, a comprehensive discussion of the characteristics and distribution of the American loess, with references to McGee, Shimek, and others.

years ago when the origin of the loess was under heated discussion. Furthermore, the emphasis in the past has been on the agencies of deposition rather than on the time of deposition. Indeed the latter question does not seem to have received much consideration, in spite of its importance in the interpreting of the climatic conditions during a part of the past.

These four hypotheses as to the time of origin of loess imply differences in its climatic relations. If loess was chiefly formed during typical interglacial epochs, or toward the close of such epochs, profound general aridity must seemingly have prevailed in order to kill the vegetation and thus enable the wind to pick up sufficient dust. If the loess was chiefly formed during times of extreme glaciation when the glaciers were supplying large quantities of fine material to out-flowing streams, less aridity would be required, but seemingly there must have been sharp contrasts between wet seasons in summer when the snow was melting and dry seasons in winter. Alternate floods and droughts would thus affect broad areas along the streams. Hence arises the hypothesis that the wind obtained the loess from the flood plains of streams at times of maximum glaciation. If the loess was chiefly formed during the rapid retreat of the ice, alternate summer floods and winter droughts would still prevail, but much material could also be obtained by the winds, not only from flood plains, but also from the deposits exposed by the melting of the ice and not yet covered by vegetation.

In support of the hypothesis of the interglacial origin of loess, Shimek and others state that the glacial drift which lies beneath the loess commonly gives evidence that some time elapsed between the disappearance of the ice and the deposition of the loess. For example, most of the locally abundant shells of snails in the loess are not of the sort now found in colder regions, but resemble those found in the drier regions. It is probable, Shimek concludes, that if they represented a glacial epoch all would be dwarfed by the cold as are the snails of far northern regions. The gravel pavements, discussed below, are pointed out by Shimek as strong evidence of erosion between the retreat of the ice and the deposition of the loess.

Turning to the second hypothesis, namely that the loess accumulated near the close of the interglacial epoch rather than in the

midst of it, we may follow Penck.[1] The mammalian fossils seem to him to prove that the loess was formed while boreal animals occupied the region, for they include remains of the hairy mammoth, woolly rhinoceros, and reindeer. On the other hand, the typical interglacial beds not far away yield remains of species characteristic of milder climates, such as the elephant, the smaller rhinoceros, and the deer. In connection with these facts it should be noted that occasional remains of tundra vegetation and of trees are found beneath the loess, while in the loess itself certain steppe animals, such as the common gopher, or spermaphyl, are found. Penck interprets this as indicating a progressive desiccation culminating just before the oncoming of the next ice sheet.

The evidence in favor of the hypothesis that the loess was formed during the maximum extension of the ice chiefly concerns its relation to the ice sheets and to the streams which flowed from the melting ice. If the great American deposits of loess do not represent the outwash from the Iowan ice, there is little else that does, and presumably there must have been outwash. Also the distribution of loess along the margins of streams suggests that much of the material came from the flood plains of overloaded streams flowing from the melting ice. Furthermore, in many places at least, the drift just beneath the loess presents little or no evidence of having been weathered or leached before the loess was laid down. Chamberlin found that many tests showed it to contain about as much calcareous material as the loess itself. This suggests that it was laid down at about the same time as the underlying drift, not notably afterward.[2] Likewise, although Shimek has emphasized the fact that most of the snails do not show depauperization, McGee reports that depauperization is evident among those found near the glacial margins, and that shells are very rare there. Both of these conditions suggest that much of the loess accumulated under glacial conditions.

Thus although there are some points in favor of the hypothesis that the loess originated (1) in strictly interglacial times, (2) at

[1] Penck's conclusions are given in full in W. B. Wright, *The Quarternary Ice Age*, London, 1913.

[2] T. C. Chamberlin, personal communication.

the end of the interglacial epochs, and (3) at times of full glaciation, each hypothesis is much weakened by evidence that supports the others. The evidence of boreal animals seems to disprove the hypothesis that the loess was formed in the middle of a mild interglacial epoch. On the other hand, Penck's hypothesis as to loess at the end of interglacial times fails to account for certain characteristics of the lowest part of the loess deposits and of the underlying drift. Instead of normal valleys and consequent prompt drainage, such as ought to have developed before the end of a long interglacial epoch, the surface on which the loess lies shows many undrained depressions. Some of these can be seen in exposed banks, while many more are inferred from the presence of shells of pond snails here and there in the overlying loess. The pond snails presumably lived in shallow pools occupying depressions in the uneven surface left by the ice. Another reason for questioning whether the loess was formed chiefly at the end of an interglacial epoch is that this hypothesis does not provide a reasonable origin for the material which composes the glacial loess deposits of important loess-covered regions. Near the Alps, where the loess deposits are small and where glaciers probably persisted in the interglacial epochs and thus supplied flood material in large quantities, this shortcoming perhaps does not appear important. In the broad Upper Mississippi basin, however, and also in the Black Earth region of Russia there would seem to be, during an interglacial epoch, no way to get the large body of material composing the loess, except by assuming the existence of great deserts to windward. But there is little or no evidence of such deserts where they could be effective. The mineralogical character of the loess of Iowan age proves that the material came from granitic rocks, such as formed a large part of the drift. The nearest extensive outcrops of granite are in the southwestern part of the United States, nearly a thousand miles from Iowa and Illinois. But the loess is thickest near the ice margins and thins toward the southwest and in other directions, whereas if its source was the southwestern desert its maximum thickness would probably be near the margin of the desert. Furthermore the similarity in calcareous content of the loess and the underlying drift, reported by Chamberlin, points

against Penck's hypothesis, for if the loess did not accumulate until near the close of an interglacial epoch, it is probable that the calcareous matter would have been largely leached from the upper layers of the underlying drift. The interglacial epochs are now known to have been sufficiently long for much weathering to take place. Thus considerable evidence seems inconsistent with the hypothesis that the loess was formed chiefly toward the close of an interglacial epoch.

There is much less evidence against the hypothesis that the great loess deposits accumulated chiefly during the maximum extension of the ice. Indeed it remains as a worthy working hypothesis. However, the question may be raised as to whether or not flood plains of streams would provide adequate supplies of materials for such widespread, rather uniform deposits as those of Russia and of Iowa and Illinois. A further question comes to mind: Would the type of vegetation which would probably occur along the ice front at its maximum extension be that of which the loess gives evidence? Indeed it seems probable that when the ice advanced, its front lay close to areas where the vegetation was not much thinner than that which today prevails under similar climatic conditions. If the average temperature of glacial maxima was only about 6°C. lower than that of today, as many authorities consider likely, the conditions just beyond the ice front when it was in the loess region from southern Indiana to Nebraska would probably have been like those now prevailing in Canada from New Brunswick to Winnipeg. The vegetation there is quite different from the grassy vegetation of which evidence is found in the loess. The roots and stalks of such grassy vegetation are generally agreed to have helped produce the columnar structure which enables the loess to stand with almost vertical surface. Thus it seems appropriate to add a supplementary hypothesis to suggest that certain phenomena would be readily explainable in case the chief accumulation was during glacial retreat, rather than at the time of maximum extension of ice.

We are now ready to consider the probability that loess accumulated mainly during the retreat of the ice. Such a retreat exposed a zone of drift to the out-blowing glacial winds. Most glacial hypotheses, such as that of uplift, or depleted carbon dioxide,

call for a gradual retreat of the ice scarcely faster than the vegetation could advance into the abandoned area. Under Huntington's solar-cyclonic hypothesis,[1] on the other hand, the climatic changes may have been sudden and hence the retreat of the ice may have been much more rapid than the advance of vegetation. Now wind-blown materials are derived from places where vegetation is scanty. Scanty vegetation on good soil, it is true, is usually due to aridity, but may also result because the time since the soil was exposed has not been long enough so that it may be covered with vegetation. Sand bars, mud flats, and flood plains are common examples. Moreover, violent winds and low temperatures may prevent the spread of vegetation. Thus it appears that unless the retreat of the ice were as slow as the advance of vegetation, a barren area of more or less width must have bordered the retreating ice and formed an ideal source of loess.

Several other lines of evidence seemingly support the conclusion that the loess was chiefly formed during the retreat of the ice. For example, Shimek, who has made almost a life-long study of the Iowan loess, emphasizes the fact that there is often an accumulation of stones and pebbles at its base. This suggests that the underlying till was eroded before the loess was deposited upon it. The first reaction of most students is to assume that of course this was due to running water. That is possible in many cases, but by no means in all. So widespread a sheet of gravel could not be deposited by streams without destroying the irregular basins and hollows of which we have seen evidence where the loess lies on glacial deposits. On the other hand, the wind is competent to produce a similar gravel pavement without destroying the old topography. "Desert pavements" are a notable feature in most deserts. The commonest winds are outward near the edge of an ice sheet, as Hobbs has made us realize.[2] They often attain a velocity of eighty miles an hour in Antarctica and Greenland.

[1] Ellsworth Huntington, *Earth and Sun*, Yale Press, New Haven, 1922; and Huntington and Visher, *Climatic Changes, Their Nature and Causes*, Yale Press, 1922.

[2] W. H. Hobbs, *Characteristics of Existing Glaciers*, 1911; "The Rôle of the Glacial Anti-Cyclone in the Air Circulation of the Globe," *Proceed. Am. Phil. Soc.*, Vol. LIV (1915), pp. 185–225.

Such winds, however, usually decline rapidly in velocity only a few score miles from the ice. Thus their effect would be to produce rapid erosion of the freshly bared surface near the retreating ice. The pebbles would be left behind as a pavement, while sand and then loess would be deposited farther from the ice where the winds were weaker and where vegetation was beginning to take root. Such a decrease in wind velocity may explain the occasional vertical gradation from gravel through sand to coarse loess and then to normal fine loess. As the ice sheet retreated, the wind in any given place would gradually become less violent. As the ice continued to retreat, the area where loess was deposited would follow at a distance, and thus each part of the gravel pavement would in turn be covered with loess.

The hypothesis that loess is deposited while the ice is retreating is in accord with many other lines of evidence. For example, it accords with the boreal character of the mammal remains as described above and of the depauperated snail fauna found in the zone nearest the ancient ice sheets. Again, the advance of vegetation into the barren zone along the front of the ice would be delayed by the strong out-blowing winds. The common pioneer plants depend largely on the wind for the distribution of their seeds, but the glacial winds would carry them away from the ice rather than toward it. The glacial winds discourage the advance of vegetation in another way, for they are drying winds, as are almost all winds blowing from a colder to a warmer region. Such winds, however, would interfere less with the northward spread of grasses propagated by root shoots and by abundant seeds than it would interfere with the spread of trees. The fact that remains of trees sometimes occur at the bottom of the loess probably means that the deposition of loess extended into the forests which almost certainly persisted not far from the ice at its maximum advance. This seems more likely than that a period of severe aridity before the coming of the glacier killed the trees and made a widespread steppe or desert. Penck's chief argument in favor of the formation of loess before the advance of the ice rather than after appears to be that since loess is lacking upon the youngest drift sheet in Europe it must have been formed before rather than after the last or Würm advance of

the ice. This argument is not convincing for two special reasons: First, on the corresponding (Wisconsin) drift sheet in America loess is present—in small quantities to be sure, but unmistakably present. Second, there is no reason to assume that conditions were identical at each advance and retreat of the ice. Indeed, the fact that in Europe, as in the United States, nearly all the loess was formed at one time, and only a little is associated with the other ice advances, points clearly against Penck's fundamental assumption that the accumulation of loess was due to the approach of a cold climate. The relative abundance of loess associated with the Iowan ice sheet would be explained by the present hypothesis if ice retreated more rapidly for a time than did any of the later ice sheets.

Thus the hypothesis that the loess accumulated chiefly during the retreat of the ice sheets appears to have enough support to merit consideration by students of loess.

MEMORIAL EDITORIAL

ROLLIN D. SALISBURY

August 17, 1858—August 15, 1922

It is with deep sorrow that the *Journal of Geology* records the death of its active managing editor, Dean Rollin D. Salisbury. After a severe illness of two and a half months, he passed away on the evening of August 15, within two days of his sixty-fourth birthday. For the past four years he had been the responsible editor of the *Journal*, while from its founding in January, 1893, he participated actively in the general responsibilities of its editorial management and had special charge of contributions relating to the physiographic aspects of geology. This special service in the dissemination of the literature of the science of the earth thus ran through a period of almost thirty years. The more than 1,300 standard articles, 2,500 abstracts and reviews, 150 editorials and shorter notices, embracing more than 24,000 pages of printed matter, which received all phases of editorial care from the reading of manuscript to the approval of the final proof, attest at once the importance and the burden of this work. Professor Salisbury himself prepared 82 contributions.

The scientific investigations of Dr. Salisbury will be reviewed in a later article more fully than is possible here. His field work was begun under the auspices of the United States Geological Survey as early as 1881 and continued until 1910. It embraced extensive studies on the glacial and other Pleistocene formations of the northern states and the lower Mississippi Valley. In connection with this, he made a report on Crowley's Ridge to the Geological Survey of Arkansas. From 1891 to 1910 he was geologist in charge of the Pleistocene Division of the Geological Survey of New Jersey, where his work on the older drift and on fluvial deposits formed near the neutral zone between marine and upland horizons was notable for its keen insight and acute discrimination. He made important contributions to the Geological Survey of Illinois and

in 1919 was appointed to the Board of Commissioners in charge of the Survey. Besides these official services he made independent investigations in several lines. He was geologist of the Peary Relief Expedition to Northern Greenland in 1895, in connection with which he studied existing glaciers under the unparalleled advantages presented in very high latitudes.

Dr. Salisbury was a very lucid writer. The reports of his researches and the texts of the several works he prepared for the general reader and for students put into the easy possession of others what he saw so clearly himself. The printed results of his studies in field and office will long stand as a lasting memorial to Professor Salisbury's industry and clarity of vision.

Large and important as were these contributions, Dr. Salisbury's greatest service to science lay in his singular success in stimulating and training young talent not only for the teaching of science but for research. This distinguished service began at Beloit College, 1883–91, was continued at the University of Wisconsin, 1891–92, and was transferred to the University of Chicago at its opening, where he took part in founding the Department of Geology thirty years ago. For nearly twenty years he was active executive of the Department and for the last four years bore its full responsibilities. In connection with this geological service he developed the Department of Geography and served as its head from 1913 to 1918, when he was made head of the Department of Geology, and the Department of Geography was transferred to one who, first as a student under him, and then as a colleague, had grown to marked efficiency. From 1899 onward Dr. Salisbury was dean of the Ogden (Graduate) School of Science of the University of Chicago. In these varied relations he came into touch with thousands of young minds and gave them effective impulses toward sound scholarship and the higher life. The ultimate effects of this work are beyond estimation. Through the growing efficiency and the rising power of the young talent thus inspired by his leadership, Dean Salisbury's greatest service to science and to humanity has only fairly begun.

T. C. C.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Harker, Alfred. *Petrology for Students.* Cambridge, 1919, 5th ed. Pp. 300, figs. 100.

A comparison of the fifth with the fourth edition of Harker's book shows the chief change to be that practically all of the American examples have been "improved out." With the exception of one chapter where nephelite- and leucite-syenites are now separated from the syenites, the two editions could be used in the same class, for though the pagination is different, the different paragraphs can be easily located. The change of the chapter heading "Diabase" to "Dolerite" will not be considered an improvement in this country. Both terms are bad, in that each has two meanings; the former being used for ophitic dike-rocks of the composition of gabbros as well as for Paleozoic basalts, the latter, originally for coarse-grained basalts, now according to British usage for the rocks we call diabase. Harker still clings to the classification of diorite as a hornblende-bearing rock (p. 63) while gabbros are defined as "characterized by pyroxenes in place of hornblende" although he recognizes the modern tendency in classifications when he says: "The distinction between the hornblende- and augite-bearing types is rather an artificial one. It was established before the strong tendency of augite to pass over into hornblende was thoroughly appreciated." Also, "The family as so defined cannot be regarded as a natural one." The feldspar of diorite is given as "andesine or labradorite or exceptionally a more basic variety," while in gabbros it is given as "labradorite, with exceptionally one more acid and occasionally orthoclase."

Hirschwald, J. *Leitsätze für die praktische Beurteilung, zweckmässige Auswahl und Bearbeitung natürlicher Bausteine.* Berlin, 1915. Pp. 36, figs. 18.

This book was primarily written for stone-workers and aims at giving the most important points needed in the selection and judging of building-stone. There is a short classification of rocks giving the desirable and undesirable characteristics of each, a chapter on the examination of stone quarries with examples of written forms for describing quarries, and chapters on the essentials of stone-testing, advantageous modes of working and using certain rocks with reference to schistosity, cleavage, etc., various uses of different kinds of stone, etc.

HOLMES, ARTHUR. *The Nomenclature of Petrology.* London, 1920. Pp. 284.

This little book is intended as an English substitute for Loewinson-Lessing's *Lexique Pétrographique*, which is now about twenty years old. It is a very convenient and useful volume, giving in brief form, definitions of most of the common terms used in petrology. The only fault that might be found with it is that it is too brief, and that the references are, in many cases, not to the work in which the term was originally given, but usually to later British authors. In other cases references are hard to find; for example, the reference for the source of umptekite is under "chibinite," and maenaite under "grorudite," but this can hardly be called satisfactory, especially since no hint is given as to the terms under which they may be found. Other references, such as "Syenodiorite, Evans, 1916," etc., are too incomplete to be traced. On the whole, however, the book is very good, and it is likely to prove useful to students by giving them the means for quickly finding unfamiliar terms.

HOLMES, ARTHUR. *Petrographic Methods and Calculations.* London, 1921. Pp. 515, figs. 83, pls. 4.

Quite different from previously published books on petrographic methods is this one by Holmes, in that very little space is devoted to optical methods. The author says in his preface, "I have tried to produce a more evenly balanced treatise which should penetrate the petrological domain, and not merely skirt its border land." Chapter i deals with Petrology, its scope, aims, and application, chapter ii with specific gravity, chapter iii (40 pp.), separation of minerals by heavy liquids, magnet, etc., chapter iv (52 pp.), optical examination of minerals, including not only optical properties but tables for the determination of minerals, chapter v (71 pp.), the examination of detrital sediments, chapter vi (19 pp.), the preparation of thin sections, chapter vii (45 pp.), microchemical and staining methods, chapter viii (38 pp.), the examination of thin sections, including a discussion of the Rosiwal and similar methods, genesis of minerals, saturated and unsaturated minerals, etc. Incidentally it is stated that "Johannsen has suggested the use of a planimeter for measuring areas of particular minerals on a drawing of a thin section made with the aid of a camera lucida. The procedure is more complicated and tedious than the ordinary linear method now in general use." But in the method mentioned no camera lucida drawing is made and the time required is less than a fourth of that of the Rosiwal. Chapter ix deals with rock textures, chapter x with chemical analyses and their interpretation and includes a discussion of the C.I.P.W. system, and chapter xi with graphical representation of chemical analyses. The book thus brings together much of the miscellaneous data so often needed by the petrographer. It will therefore be examined with interest and profit by all advanced workers in the science.

HOMMEL, W. "*Systematische Petrographie auf genetischer Grundlage,*" Vol. I, *Das System.* Gebrüder Borntraeger, Berlin, 1919. Pp. xii+174, figs. 5, pls. 5.

Hommel proposes a double-barreled system of classification, in that he represents a rock by a formula composed of two parts. The first, which he calls his "Molekularformel," is derived directly from the chemical analysis and represents the molecular proportions of the various oxides. The second, or "Konstitutions formel," represents the percentages of certain minerals calculated from the chemical analysis. The percentages of the computed minerals, however, resemble those of the normative minerals of the C.I.P.W. system. since they generally do not represent the amounts actually present in the rock. As in the C.I.P.W. system, the feldspars are calculated from the amounts of K_2O, Na_2O, and CaO present in the analysis. Orthoclase is considered pure K_2O, Al_2O_3, $6SiO_2$, and all the soda is calculated as part of the plagioclase. As a matter of fact, a considerable amount of the soda may occur in the orthoclase or microcline as lamellar intergrowth, either visible or invisible. Where all is calculated in the plagioclase, the resulting mineral is too near the soda end. Potash in muscovite is disregarded, and the only lime or alumina used for the dark minerals is that which occurs in excess of the requirement of the theoretical feldspars.

So far as the first part of the formula is concerned, no objection can be made to it, since it is confessedly chemical. It has the advantage of simplicity over the C.I.P.W. system, and can be shown in a diagram. Whether it is better than Osann's system is a question. Certainly Osann's latest modification (*Der chemische Faktor in einer natürlichen Klassifikation der Eruptivgesteine*, Heidelberg, 1919. Review to follow in this *Journal*) offers a rapid means for finding rocks of similar composition. Since only Part I of Hommel's book is printed, however, it is possible that similar groups of rocks may appear later.

Hommel's system can best be illustrated by an example. The kern granite of the Brocken in molecules, reduced to 100, gives SiO_2 80.2, TiO_2 —, Al_2O_3 8.6, Fe_2O_3 0.5, FeO 1.5, MgO 0.4, CaO 1.4, Na_2O 3.3, K_2O 4.1. Hommel's formula for this rock is:

$$80.2\sum_{1.2}^{3.3} 4.1\ \dot{F}_2\ \ddot{e}\ \ddot{m}c\ 2.6 = +31\ P\ \left[\dot{O}_{33}\dot{O}l^{\circ}_{31}\right]\dot{\beta}\ 5.$$

The first part is the molecular formula and is obtained as follows: The figures 80.2 represent the amount of the silica molecules (plus TiO_2 and P_2O_5) as computed above. The large figures immediately after the sign Σ represent the K_2O molecules; the Na_2O mol. and the CaO mol. in feldspar being represented by the figures above and below the sign. The CaO figures necessarily cannot be greater than the amount of Al_2O_3 remaining after enough has been used to satisfy the soda and potash. Excess CaO is added to the mafic minerals as *c*. The mafic constituents are represented by *e* for Fe_2O_3, *f* for FeO+MnO, *m* for

MgO, and *c* for the remaining CaO. If all of the CaO was used for feldspar, the excess of Al_2O_3 is represented by *t* among the mafic constituents. If there is insufficient Al_2O_3 to satisfy the alkalies, the remaining Na_2O is indicated by *n* and it also is placed among the ferromagnesian constituents. In the above example, $K_2O + Na_2O = 4.1 + 3.3 = 7.4$, corresponding to 7.4 Al_2O_3 leaving 1.2 Al_2O_3 to unite with CaO for the anorthite radical. The remaining 0.2 CaO is represented by *c* among the mafic constituents. The ferromagnesian constituents are given in the order of decreasing abundance, and their sum is represented by the figure following (here 2.6). The relative abundance is indicated in the symbol, thus

fm indicates an FeO/MgO ratio below 5 FeO/4 MgO.

$\dot{f} = 1\frac{1}{2}$ f, therefore $\dot{f}$m shows a ratio between 4FeO:3MgO and 3FeO: 2MgO.

$\ddot{f} = 2$ f, or $\ddot{f}$m indicates the ratio of 2/1.

F = 3f, and Fm = 3 FeO to 1 MgO.

$\dot{F} = 4$f, and $\dot{F}$m = 4/1.

$\ddot{F} = 5$f, and $\ddot{F}$m = 5/1.

$F_2 = 6$f,

$\ddot{F}_2 = 8$f,

$\dot{F}_3 = 10$f,

$F_4 = 12$f, etc., etc.

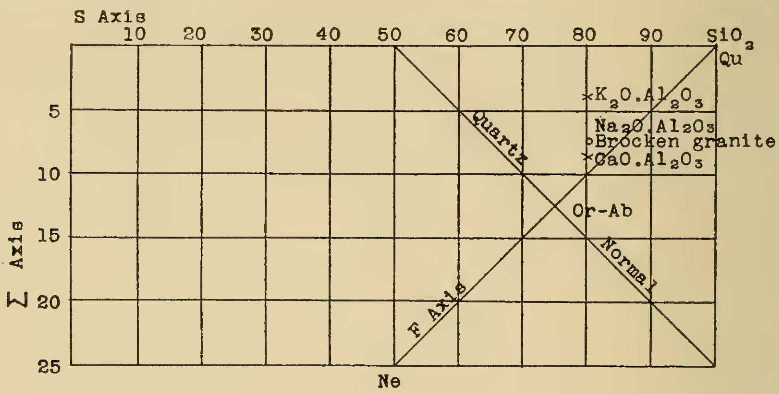
Since the remaining constituents in the order of decreasing abundance in the example given are FeO = 1.5, Fe_2O_3 = c.5, MgO = 0.4, and CaO = 0.2 (the ratios being therefore as 7 : 2.5 : 2 : 1 approximately), they are represented by $\dot{F}_2 : \ddot{e} : \ddot{m} : c$. (These symbols are complicated. Why not use the ratio directly as subscripts; thus here $F_{1.5} . e_{0.5} . m_{0.4} . c_{0.2}$, or even the simplified similar ratios $F_7 . e_{2.5} . m_2 . c$).

The rock may be plotted on rectangular co-ordinates as shown by the figure. The horizontal line (*S* axis) represents the silica content. The vertical line through 50 per cent is the Σ axis and is the measure of the feldspar content. It is drawn at double the scale of the *S* axis because for each molecule of alkali or lime, a molecule of Al_2O_3 is also automatically included. Further, there are two diagonal lines at 45° through the 50 per cent and 100 per cent points on the *S* line; the former is called the quartz normal, the latter the *F* axis.

The Brocken granite is thus plotted by measuring from the 80.2 point on the *S* axis downward 4.1 for K_2O. This *K* point is indicated by an *x*. A further distance of 3.3 for Na_2O is laid off on the same line and the point is marked by a circle. This is called the Locus of the rock (*Ort des Gesteins*). Finally 1.2 is

plotted on the extension of the line for CaO, and this is also marked by an x. This is the Σ point. The horizontal distance of the Σ point from the F axis (in units as measured on S) gives the amount of the ferromagnesian constituents. The amount of free (theoretical) quartz is given by the horizontal distance of the Locus of the rock from the "Quartz normal." (As measured on the S scale, the reading is to be multiplied by 2.) In the case of the Brocken granite this distance is 15.4, therefore the theoretical amount of free quartz is 30.8.

Since the quartz normal and the F axis are both at 45°, the readings may be made along the downward extension of the line passing through the locus of the rock, instead of along the horizontal.



The second part of the formula, the "Konstitutionsformel," represents theoretical minerals. The method for computing the free quartz follows from the diagram. Twice the sum of the alkalies is subtracted from the silica value less fifty (the diagonal line starting at the 50 point), and the result is multiplied by two.

Free quartz $=2[(SiO_2-50)-2(K_2O+Na_2O)]$, where SiO_2, K_2O, etc., are molecular values. The Brocken granite therefore gives $2[(80.2-50)-2(4.1+3.3)]=+30.8$ or approximately $+31$. The plus sign gives the position of the rock above the quartz normal in the diagram, and shows free quartz. Below the line is shown by a minus sign. This indicates nephelite, olivine, etc. The letter P (plutonic) indicates the texture. O stands for orthoclase. Its value is obtained by multiplying the K_2O mol. by 8, since the formula is $K_2O.Al_2O_3.6SiO_2$. ($K_2O=4.1$, $O=8\times 4.1=32.8$ or ca. 33). The plagioclase indicated by the molecular formula is 3.3 Na_2O, 1.2 CaO, or basic oligoclase, Ab_6An_1. The molecular value of the albite is eight times the Na_2O, but the anorthite, with the formula $CaO.Al_2O_3.2SiO_2$ is only four times the CaO. ($3.3\times 8+1.2\times 4=31.2$). The symbol for basic oligoclase is Ol°. Beta indicates biotite, and 5 per cent represents the remainder left for this mineral. It amounts, of course, from the formula $RO.SiO_2$ to twice the F value.

With insufficient Al_3O_3, the symbol Δ is used in the formula instead of Σ, and the aegirite molecule takes the place of the anorthite. Thus Δ 4 means

$4(K_2O.Al_2O_3)$. $6(Na_2O.Al_2O_3)$. $2(Na_2O. Fe_2O_3)$. These rocks may contain free quartz (or nephelite). Where there is quartz it is to be noted that only four molecules of SiO_2 are required to one of Na_2O, consequently there will be more quartz than in the case where all the soda goes into feldspar. The formula for the quartz, in this case, consequently, reads $2[(SiO_2\text{mol.}-50)-\{2(K_2O\text{ mol.}+Na_2O\text{ mol.})+\text{aeg. mol}\}]$.

With insufficient silica, so that a negative result is obtained by the quartz formula, it is evident that olivine or nephelite (or leucite) is present. The formula here is divided instead of multiplied by 2, and we have nephelite $=\frac{SiO_2-50-[2(K_2O+Na_2O)+\text{aeg. mol.}]}{2}$ (the alkali molecules are those in feldspar and feldspathoid only).

Examples of the nephelite rocks and rocks with insufficient alumina would make this abstract too long.

The third section of the book consists of a natural classification of rocks on genetic principles. A detailed description is impossible here and the reader is referred to the original work which is full of suggestions. Briefly, rocks are divided into five groups: (1) the orthogene class of rocks includes those formed by slow cooling in the interior of the earth; (2) the paragene class originated in a relatively rapid cooling of the magma during the period of crystallization of olivine, consequently that mineral could not settle out but is represented by its recrystallizations as diopside, etc.; (3) the hypogene class includes extrusive rocks formed under conditions of rapid cooling, relief from pressure, and movement; (4) peratogene rocks are those altered by metamorphism and include the crystalline schists; (5) diagene rocks include the sediments. The first four groups are subdivided into ten zones each, each zone representing a distinct temperature-interval through which the magma passed on cooling, and marked by the separation of typical and chemically well-defined minerals. There are thus the zones of (1) chromite, (2) olivine, (3) enstatite, (4) diopside, (5a) labradorite, (5b) nephelite, (6) labradorite-andesine, (7) andesine, (8a) andesine-oligoclase, (8b) oligoclase, (9) orthoclase, (10) quartz.

The book is one which will repay very careful study in every part. While one might wish that the "Konstitutionsformel" represented actual rather than theoretical minerals, one can easily understand how the former might make difficulties in certain cases. Undoubtedly this book is one of the most important works on petrography that has appeared in recent years.

Iddings, J. P., and Morley, E. W. "A Contribution to the Petrography of the South Sea Islands," *Proc. Nat. Acad. Sci.*, IV (1918), 110–17.

This is a preliminary statement of the geological structure and character of seven islands of the South Seas, including Tahiti, Moorea, and the Society Group. Thirty new chemical analyses are here published for the first time.

The rocks of Tahiti are almost wholly olivine basalts, some with nephelite or analcite. Trachytic and phonolitic lavas occur on five of the seven islands. A nephelite-latite, consisting of alkalic feldspar and andesine with some nephelite and sodalite and abundant hornblende, much titanite, and few augites and micas is given the new name of *tautirite*, from the valley, Tautira, Taiarapu, in which it occurs. The mode is not given but the norm contains Or 31.1, Ab 28.3, An 13.3, and Ne 10.8.

JEHU, T. J., and CAMPBELL, ROBERT. "The Highland Border Rocks of the Aberfoyle District," *Trans. Roy. Soc. Edinburgh*, LII (1917), 175–212, figs. 10, pls. 6.

A series of grits, shales, limestones, cherty shales, graphitic shales, and various igneous rocks, in places highly altered, extending from Stonehaven to Arran, is grouped under the term "The Highland Border Rocks." They are here arranged in two divisions. The sediments of the Lower Series are either Upper Cambrian or transitional between Cambrian and Ordovician, and are thought to have been deposited in clear water near the verge of sedimentation. The lavas indicate submarine eruptions. The Upper Series, which belong higher in the Ordovician, include limestones, hornblende- and chlorite-schists, and igneous rocks.

JOHANNSEN, ALBERT. *Essentials for the Microscopical Determination of Rock-forming Minerals and Rocks in Thin Sections.* Chicago, 1922. Quarto, pp. vi + 54, figs. 24, pls. 6, and a folding table.

This laboratory manual contains practically all of the data originally published in the writer's *Determination of Rock-forming Minerals*, and in addition gives modes of occurrence and many more points of separation between similar minerals. Only a few very rare species, such as johnstrupite, mosandrite, laavenite, etc., have been omitted, but by uniting the tables which contained minerals having birefringences greater or less than quartz, and refractive indices greater or less than Canada balsam, much repetition has been avoided, and the number of pages has been materially reduced. Orthorhombic minerals have been united with the other biaxial minerals, since sections which cut all of the crystallographic axes in this system show inclined extinction, but the extinction angles are given in the descriptions. The separation lines between the various plagioclase feldspars have been changed from those given in the former book to 5, 27½, 50, 72½, and 95 per cent anorthite. Albite and anorthite have been limited to a variation of only 5 per cent since these names are also applied to the pure end members, and compound names, such as oligoclase-albite, labradorite-bytownite, etc., have been omitted. The section on the determination of the feldspars has been but little reduced, but that on optical

methods has been condensed as much as possible, since this data is given elsewhere. The alphabetical list of minerals has been much extended, and is now placed at the back of the book in such a position that it may be consulted without turning pages. Finally, a short section on the classification of igneous rocks according to the author's system has been added. As given here, this classification is essentially the same as that published in the *Journal of Geology* several years ago, except that the whole of the monzonitic series, with the exception of monzonite and quartz-monzonite, has been omitted.

KAISER, ERICH. "Der Eläolithsyenitlakkolith der Serra de Monchique im südlichen Portugal," *Neues Jahrb.*, B. B., XXXIX (1914), 225–67, pls. 2, profiles 2, map 1, figs. 6.

Discusses the structure of the Serra de Monchique in southern Portugal, with special reference to the nephelite-syenite central mass. He considers this a laccolith that was intruded during the period of folding. The main foyaitic mass with border pulaskites, and various dike-rocks are briefly described.

KAISER, ERICH. "Über ein Demonstrationsmikroskop für den mineralogischen und petrographischen Unterricht," *Zeitschr. f. Kryst.*, LIII (1914), 397–403.

Describes a microscope for demonstration purposes. It has a large, rotatable stage with ten openings, so that that number of thin sections can be placed on it at one time, and the specimens observed one after the other. A glass plate prevents the disturbance of the sections by students. Since the preparations cannot be turned there is provided a means for rotating the tube of the microscope.

KAISER, ERICH. "Studien während des Krieges in Südwestafrika," *Zeitschr. d. deutsch. geol. Gesell.*, LXXII (1920), 50–76.

The three studies included in these papers are: (1) Assimilationsercsheinungen an den Elaeolithsyeniten des Granitberg in südlichen Namib," (2) "Zur Kenntnis der Hohlformen, Eindeckungen, Ausfüllungen und Aufschüttungen der Trockengebiete," and (3) "Kalkkrusten." In the first paper the nephelite-syenite stock of Granitberg, in southern Namib, is described. Besides the normal rock there are certain other types which cannot be explained by normal differentiation. The contact of the main mass is irregular and blurred, owing to the penetration of the country rock by numerous veins and apophyses of the igneous rock, thus giving the impression of an irregular breccia penetrated by the nephelite-syenite. But it is not a breccia in the ordinary sense since the fracturing was caused by the intrusion itself. Both intrusive and intruded

rock are altered, the character of the resultant depending upon the nature of the country rock. Against sandstone and arkoses there is a decrease in the feldspathoids and a transition to syenite and even to quartz-bearing and nephelite-free alkali granites. Where the igneous rock is in contact with the dolomitic Cambrian rocks there is an increase in the amount of nephelite and the grain is coarse, in some cases giving nephelite-syenite-pegmatite phases with nephelites several centimeters in size. Such changes in the character of the rock cannot be explained by differentiation alone. Kaiser thinks that assimilation of the country rock is clearly indicated, although he supposes that there was also subsequent differentiation. He warns, however, against using such local occurrences either for or against the assimilation theory of magmas in general. The mechanics of the intrusion, he thinks, agree with Daly's theory of magmatic stoping. He believes the magma reached its present position not by intrusion between strata, but by forming a place for itself.

KAISER, ERICH. "Bericht über geologische Studien während des Krieges in Südwestafrika," *Abhandl. d. Giessener Hochschulgesell.*, II (1920). Pp. 57, pls. 6, figs. 4

A general geological description of Namib, an interesting petrographic description of which is given in greater detail in the preceding paper. The scope of the work is indicated in the chapter headings, some of which are crystalline schists, Cambrian, eruptive rocks, Tertiary, alteration of the Tertiary land surface, underground water, mineral occurrences, etc.

KATŌ, TAKEO. "Microscopic Secondary Sulphide Enrichment in the 'Kuromono' Ore from the Kosaka Mine, in the Province of Rikuchü, Japan, *Jour. Geol. Soc. Tokyo*, XXV (1918), 1–7, pls. 1.

KATŌ, TAKEO. "A Contribution to the Knowledge of the Mesozoic Igneous Rocks Developed Around the Tsushima Basin, Japan, *Jour. Geol. Soc. Tokyo*, XXVII (1920), 1–22, 23–38, pls. 4, figs. 2.

A porphyrite complex with associated tuff beds, late Jurassic in age, was invaded by a series of igneous rocks in the following order: (1) effusive quartz-porphyry; (2) intrusive quartz-masanite, masano-tonalite, etc., with melanocratic marginal facies; (3) tsingtauites and masano-tsingtauites; (4) dikes of masano-hornblendite; (5) aplitic and pegmatitic rocks. The rocks of (1) and (2) were probably derived from the same magma basin; (2), (3), (4), and (5) are clearly related. Sporadic corroded quartz crystals in some portions of the

porphyrite as well as those in many lamprophyres are thought to have sunk from the overlying acid magma layers, in which they were beginning to form, into the basic lower layers from which the basic rocks were derived.

KATŌ, TAKEO. "A Contribution to the Knowledge of the Cassiterite Veins of Pneumato-Hydatogenetic or Hydrothermal Origin, *Jour. Col. Sci. Imp. Univ. Tokyo*, XLIII (1920), Art. 5. Pp. 60, map 1, pls. 6, figs. 11.

Largely economic, although a considerable number of pages are devoted to igneous rocks. Among these are diorite, gabbroid-diorite, diorite-mylonite, and a rock to which the new name "akenobeite" is given. Dike-rocks are hornblende-hypersthene-andesite, garnetiferous-felsite-porphyry, felsite, porphyrites, and diabase, and there is extrusive rhyolite. The rocks are described in some detail but neither chemical nor modal analyses are given. The akenobeite is a quartz-monzonite-pegmatite or -aplite, according to Kato. It consists of tabular crystals of feldspar in haphazard orientation with the interstices filled with an aggregate of quartz. The feldspar is orthoclase and oligoclase, the latter always in excess. How much in excess is not stated, so it is a question whether the rock might not be called a granodiorite-aplite. Biotite is very subordinate and occurs in minute flakes in the feldspars or attached to its borders. In the system of the reviewer it belongs to Class 1, Order 2, Family 7 (new form), and probably in 7″. The amount of quartz is not stated, but from the two photographs given it appears to amount to 15 or 20 per cent.

KLEMM, G. "Die Granitporphyre und Alsbachite des Odenwaldes," *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, IV Folge, Hf. 35, 1914. Pp. 10–50, pls. 2, fig. 1.

In the crystalline schists of the Odenwald there are various dikes of anorthoclase-granite-porphyry and of alsbachite. Of the former rock there are twelve chemical analyses, eight of them apparently new, and of the latter, three, of which two are new. Five new analyses of dike granites are also given. All the analyses are re-computed into Osann's system.

KLEMM, G. "Bemerkungen über die im Gabbro des Frankensteins gangartig aufsetzenden Gesteine und über seine Einschlüsse von Korundfels," *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, IV Folge, Hf. 35, 1914, 5–9.

Describes certain corundum-bearing rocks occurring in the Frankenstein gabbro. The author disagrees with Kalkowsky, who regards them as diff-

erentiation products of the gabbro magma, but considers them metamorphosed inclusions of sedimentary rocks which were resorbed by the gabbro and later recrystallized.

KLEMM, G. "Über die angebliche Umwandlung von Andalusit in Disthen in den Hornfelsen des Schürrkopfes bei Gaggenau in Baden," *Zeitschr. d. Deutsch. Geol. Gesell.*, LXVIII (1916), 86–92.

Eisele regarded the disthene in the hornfels from Schürrkopf in Baden as due to alteration of andalusite by orogenic pressures which were post-contact-metamorphism; Klemm regards the two minerals as contemporaneous products.

KLEMM, G. "Zur Errinerung an Richard Lepsius," *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, V Folge Hf. 1, 1915, 5–22. With portrait and bibliography.

KLEMM, G. "Die korundführenden Hornfelse und die Schmirgelgesteine von Laudenau und Klein-Gumpen bei Reichelsheim im Odenwald und ihre Nebengesteine," *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, V Folge, Hf. 1, 1915, 23–41, pl. 1.

This is a more detailed description of the corundum-bearing rocks of the Odenwald, mentioned in the third preceding abstract. Ten new analyses are given.

KLEMM, G. "Über den 'Variolit von Asbach,'" *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, V Folge, Hf. 2, 1916 (1917), pl. 1.

The "variolite" from Asbach, called diabase by Chelius, is here determined as malchite. The varioles, representing fillings of vesicles, vary in size from hazel-nuts to walnuts, occasionally to the size of eggs. They consist of quartz feldspar, iron ore, and epidote.

KLEMM, G. *Blatt Neunkirchen.* Erläuteru. z. Geol. Karte Hessen. 2d ed. Darmstadt, 1918. Pp. 81, pl. 1.

In this general geological report on the quadrangle lying between lat. 49°48′ and 49°32′, in Hessen, there are short descriptions of many igneous rocks, and analyses of 4 hornfelses, 2 amphibolites, 9 gabbros, 3 hypersthene-gabbros, 3 serpentines, 4 diorites, 14 granites, 5 granite-porphyries, 2 granophyres, 9 malchites, and 6 odinites.

Klemm, G. "Über die Enstehung der 'Felsenmeere' des Felsberges und anderer Orte im Odenwalde," *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, V Folge, Hf. 3, 1917 (1918), 3–11, pls. 2.

Considers these particular rock-streams as due to removal of interstitial weathered material. The blocks lie practically in the positions where they were originally formed.

Klemm, G. "Der Granatfels von Gadernheim im Odenwalde und sine Nebengesteine," *Notizbl. d. Vereins f. Erdk.*, etc., z. Darmstadt, V Folge, Hf. 4, 1919, 3–32.

The flaser granite of Gadernheim shows an original contact at the south and east against metamorphosed sediments. This metamorphism was produced by gabbro which altered the sediments to garnetfels, cordierite-hornfels, biotite-hornfels, amphibolite, graphite-schist, and graphite-quartzite. The gabbro itself was altered by endogene contact action to hornblende-gabbro with a dioritic selvage.

Kolderup, Carl Fred. "Egersund," *Norges Geol. Undersök*, No. 71, 1914. Pp. 60, pls. 4, map 1.

A geologic report on a quadrangle in the southwestern part of Norway, about 60 km. SSE. of Stavanger. The principal part of the area is composed of labradoritites and pyroxene-poor norites. The composition of one of the latter is given (p. 18) as labradorite 92 per cent, pyroxene 7 per cent. and ilmenite 1 per cent. There is a smaller area of mangerites and norite-mangerites. Among the dike-rocks are mangerite, birkremite, quartz, ilmenite, granite-pegmatite, and diabase.

Kolderup, Carl Fred. "Fjeldbygningen i strøket mellem sørfjordem og Sammangerfjorden i Bergensfeltet," *Bergens Museums Aarbok*, 1914–15, No. 8. Pp. 257, figs. 91, colored pls. 2, maps 3.

The district of the Bergen arches is characterized by a peculiar arrangement of the various formations in curves. The rocks are dynamo-metamorphosed and are in part sedimentary and in part igneous. Phyllites are the most common sediments, and consist of quartz and muscovite with various accessories. In the phyllite zone occur serpentines, soapstones, green-schists, saussurite-diabases, saussurite-gabbros, labradoritite, norite, mangerite, and birkremite. The serpentines are considered metamorphosed igneous rocks, probably peridotites or pikrites. The green-schists were probably originally basic volcanic

rocks and tuffs. In the western part of the area are Middle Silurian limestones, metamorphosed to marble. Younger than the marble for it contains fragments of this rock, is the polymict conglomerate. It is probably a volcanic conglomerate whose cement originally was a tuff. The "gray granite" of Reuss is considered a pressed granite.

The structure of the area indicates that the metamorphism must have taken place in the upper part of the earth's crust where one-sided pressure, low temperature, and a considerable saturation with water were factors. The rocks of the inner arch are more strongly compressed than those of the outer, but the materials are of approximately the same kind.

KOTŌ, BUNDJIRO. "The Great Eruption of Sakura-jima in 1914," *Jour. Col. Sci., Imp. Univ. Tokyo,* XXXVIII (1916). Pp. 237, pls. 23, map 1, figs. 46.

Sixty-eight pages of this elaborate report are devoted to petrography. The descriptions are accompanied by 61 photomicrographs on 8 photogravure plates, which are beautifully clear and of considerable help. The author states that "the characterization of the rocks is merely of preliminary qualitative nature." It is to be hoped that quantitative determinations may be published later. The older lavas of the volcano are hypersthene-andesites, and are *dull* black or light brown porous and light in weight; the later lavas are *pitch* black, slaggy, and heavy, and are hypersthene-bearing pyroxene-andesites with sporadic olivine. The lavas of 1914 are also olivine-bearing hypersthene-andesites and are like those of 1779. Among the inclusions in the lava are fragments of earlier segregations, among them a lava composed principally of anorthite (printed anorthosite by mistake on p. 191) with interstitial orthoclase (?). This rock is called microtinite but deserves a new name, since microtinite as described by Lacroix was neither a pure nor nearly pure anorthite rock. No quantitative data as to the relative amounts of the two feldspars are given. The name *ceramicite* is given to porcelain-like ejectamenta which contain cordierite as the characteristic component. The other constituents are basic plagioclase and colorless glass, with subordinate hypersthene. Quartz is said to be totally wanting. With 23 beautiful photogravure plates, one may overlook the muddy half-tones which disfigure the text.

KŌZU, S. (1) "The Dispersion Phenomena and the Influence of Temperature on the Optic Axial Angle of Sanidine from the Eifel;" (2) "The Dispersion Phenomena of Some Monoclinic Feldspars," *Mineralog. Mag.,* XVII (1916), 237–52, 253–73.

Many valuable determinations on the optic axial angles and dispersion in feldspars, which would be more valuable if chemical analyses of the materials used were given.

LACROIX, A. "Les roches basiques non volcaniques de Madagascar," *Comptes Rendus*, CLIX (1914), 417–21.

Anabohitsite is a new name given to a "pyroxenite" with olivine, hypersthene, hornblende, and 30 per cent ilmenite and magnetite. It forms the periphery of the gabbro massif in Anabohitsy. The amount of olivine is not stated. Why not a peridotite? An analysis is given.

LACROIX, A. "Sur un type nouveau de roche granitique alcaline, renfermant une eucolite," *Comptes Rendus*, CLX (1915), 253–57.

A rock composed of much quartz, alcalic feldspar (microperthitic soda-orthoclase or anorthoclase with albite, in other cases albite alone), aegirite, riebeckite, and eucolite, occurring either fine-, medium-, or coarse-grained, is given the name *fasibitikite*. It is compared with rockallite. A chemical but no modal analysis is given.

LACROIX, A. "Sur quelques roches volcaniques mélanocrates des Possessions françaises de l'océan Indien et du Pacifique," *Comptes Rendus*, CLXIII (1916), 177–83.

Describes and gives analyses of two rocks which "are more calcic than feldspathic picrites, generally a little more ferruginous, and a little richer in silica. They are separated from the picrites in that their pyroxene is in excess over olivine. Further the quantity of light-colored constituents is often a little greater." No mineral percentages are given, consequently it is difficult to place it. Possibly a labradorite (?) bearing picrite. To it is given the new name *ankaramite*.

LACROIX, A. "La constitution des roches volcaniques de l'Extreme Nord de Madagascar et de Nosy bé; les ankaratrites de Madagascar en général," *Comptes Rendus*, CLXIII (1916), 253–58.

Melanocratic nephelite-basalts with considerable feldspar and phenocrysts of olivine, titaniferous augite in the form of microlites, ilmenite, often perofskite, and biotite are given the new name *ankaratrite*. The nephelite never forms more than 10 to 15 per cent of the rock and is in many cases accompanied by melilite. With simply a description for a definition, its relationship to other rocks is indeterminable.

A granular rock formed of augite and nephelite with a little olivine, biotite, apatite, and some orthoclase is called *fasinite*. Rosenbusch's *definition* of bekinkinite would cover this rock, but Lacroix says the *rock* from Bekinkiny

generally contains plagioclase, is always richer in hornblende, and has part of the nephelite changed to analcite. The unfortunate usage of giving locality names to new rock types is ever a cause for confusion. Should the original definition be considered the standard, or must a rock possess every accessory of the original rock to be of the same type, that is, should the words of the definition or the rock from a certain locality be the standard? If the latter, then practically every outcrop should have a new name, for slight variations will always be found.

LACROIX, A. "Les syénites à riebeckite d'Alter Pedroso (Portugal), leurs formes mésocrates (lusitanites) et leur transformation en leptynites et en gneiss," *Comptes Rendus*, CLXIII (1916), 279–84.

Under *lusitanite*, after the name of the country where found, there is described a mesocratic riebeckite-aegirite-syenite. Where new names are based upon variations in the mineral percentages, modal percentages should be given.

LACROIX, A. "Les laves à haüyne d'Auvergne et leurs enclaves homoeogènes," *Comptes Rendus*, CLXIV (1917), 581–87.

Ordanchite is applied to certain hauynite-tephrites from la Banne d'Ordanche. Phenocrysts of plagioclase ("oscillent entre le labrador et l'andésine"), blue hauynite, more or less corroded hornblende, and augite are visible to the unaided eye. Microscopically there are seen in addition titaniferous magnetite, titanite, apatite, and rarely olivine. *Tahitite*, after its occurrence on Tahiti, is a lava resembling ordanchite but more alcalic. Lacroix considers it a microlitic form of nephelite-monzonite. It contains phenocrysts of hauynite in a vitreous groundmass of microlites of augite, titaniferous magnetite, hauynite, and perhaps a little orthoclase and leucite. *Mareugite* is a name given to a medium-grained rock from Mareuges, Auvergne, which contains 60 per cent light minerals (bytownite and hauynite). The dark minerals present are not mentioned, but in an associated rock, called type two, they are hornblende, augite, titaniferous magnetite, and a little blue hauynite, and therefore they apparently also occur in the mareugite.

LACROIX, A. "Les laves leucitiques de la Somma," *Comptes Rendus*, CLXV (1917), 481–87.

Vesuvites are the leucite-tephrites from Vesuvius. Four apparently new analyses are given. Nine analyses of "ottajanites" are also given. They contain more plagioclase and less leucite than the vesuvianites, but since no proportions are given the dividing lines cannot be stated. Terms such as more, less, little, and much are of no value for comparison.

Lacroix, A. "Les roches grenues d'un magma leucitique étudiées à l'aide des blocs holocristallins de la Somma," *Comptes Rendus*, CLXV (1917), 205–11.

Ottajanites are leucite-tephrites having the chemical but not the mineralogical composition of sommaites. They are microlitic and contain leucite and plagioclase. *Vesuvites* are the leucite-tephrites of Vesuvius. These are described in more detail in a later publication (see next abstract). *Puglianites* are coarse-grained rocks composed of automorphic augite in a groundmass of leucite and anorthite. Certain varieties contain a little biotite, hornblende, and orthoclase. *Sebastianites* are like the puglianites chemically but are different mineralogically. They are composed of more or less automorphic anorthite, with a little augite, apatite, and biotite. Leucite is absent, all the potash being in the biotite. Chemical analyses but no modal percentages are given.

Lacroix, A. "Les formes grenues du magma leucitique du volcan laziale," *Comptes Rendus*, CLXV (1917), 1029–34.

Braccianite is applied to certain leucitites from the Lake of Bracciano but why given a new name is not clear, except to distinguish them from the Capo di Bove leucitites.

Lacroix, A. "Dacites et dacitoïdes, à propos des laves de la Martinique," *Comptes Rendus*, CLXVIII (1919), 297–302.

According to Lacroix, petrographers classify as dacite only those quartz-bearing andesites which have phenocrysts of quartz; those having quartz in the groundmasses or hidden in glassy groundmasses, and therefore only shown chemically, he says are called andesites. The latter rocks he would call dacitoides. He would extend the term to cover, not only the extrusive equivalents of the quartz-diorites, but also quartz-gabbros, in that he would have oligoclase-, andesine-, and labradorite-dacitoides, to the further confusion of present nomenclature. (H. S. Washington, *Amer. Jour. Sci.*, L [1920], 456, objects to these terms and uses Rosenbusch's term hyalodacite.)

Lacroix, A. "La constitution minéralogique et chimique des laves des volcans du Tibesti," *Comptes Rendus*, CLXIX (1919), 169–75.

In this paper *basanitoïdes* is proposed for basanites in which the nephelite is not crystallized but remains "potential in the glass." Chemically they are basanites.

LAITAKARI, AARNE. "Einige Albitepidotgesteine von Südfinnland," *Bull. Comm. Geol. Finlande*, No. 51, 1918. Pp. 13, figs. 5.

The term *helsinkite* is proposed for a haphazard-textured dike-rock, consisting of albite and epidote, and in some cases quartz (quartz-helsinkite). There is, in some cases, a little microcline, biotite, apatite, and iron ore. The amount of epidote varies from 15 to 35 per cent. In the specimen analyzed there is about 31 per cent epidote and 67 per cent feldspar, of which microcline forms less than 5 per cent (see review of Mäkinen), consequently it belongs, in the reviewer's system, to 2112 (new form). Both albite and epidote are thought to be primary magmatic minerals, the CaO having formed epidote rather than anorthite in plagioclase on account of greater water content and lower temperature of crystallization than the surrounding granite.

LAITAKARI, AARNE. "Über die Petrographie und Mineralogie der Kalksteinlagerstätten von Parainen (Pargas)," *Bull. Comm. Geol. Finlande*, No. 54, 1921. Pp. 113, figs. 40, pls. 3.

The island of Ålö, in South Finland, consists principally of migmatite, a mixture of granite and gneiss. Within this rock are long, narrow lenses of limestone, calcareous gneiss, and amphibolite, which represent remnants of strata which were infolded in the igneous rock. Cutting all these rocks there are granitic and basic dikes. A short introduction of 5 pages, descriptions of rocks 28 pages, descriptions of minerals 57 pages, contact action 7 pages, mineral paragenesis and metamorphism of the limestone 5 pages, and a bibliography of 7 pages comprise the report.

LARSEN, ESPER S. "The Microscopic Determination of the Nonopaque Minerals, *Bull. 679, U.S. Geol. Survey*, Washington, 1921. Pp. 294.

In this very valuable bulletin, Mr. Larsen gives data for determining by their refractive indices all of the transparent minerals recognized by Dana in his *System of Mineralogy* as well as a considerable number not given by him. Thus, if the optical properties are known, there is afforded a rapid means for determining the minerals by immersion in liquid media of known indices. Furthermore, about 125 pages give the results of new measurements of optical constants of about 500 species for which data was not previously available. The bulletin is invaluable and should be in the hands of every petrographer.

LARSEN, ESPER S., and HUNTER, J. F. "Melilite and Other Minerals from Gunnison County, Colorado," *Jour. Washington Acad. Sci.*, IV (1914), 473–79.

While this paper is principally mineralogic, here is first proposed the new name *uncompahgrite*, from the Uncompahgre quadrangle, Colorado, where the

rock was found. It is a coarse-grained rock made up of about two-thirds or more melilite, with considerable pyroxene, magnetite, perofskite, and apatite, while in places biotite, calcite, and other minerals occur. In texture it is commonly coarse, but varies. Cleavage pieces of melilite a foot across and mottled by inclusions of other constituents are not uncommon. The finest grained rock is hypautomorphic-granular with crystals averaging 1 mm. across. In the new system of the reviewer, the rock belongs to 2125.

LARSEN, ESPER S., and MANSFIELD, GEORGE R. "Nepheline Basalt in the Fort Hall Indian Reservation, Idaho," *Jour. Washington Acad. Sci.*, V (1915), 463–68.

The mode of this nephelite-basalt, as given by Mr. Larsen, is nephelite 20, diopside 39, forsterite 26, biotite 8, magnetite 3, ilmenite 1, and apatite 1 per cent. In the reviewer's system it belongs in 3125 (new form).

LEHMANN, E. "Die Ermittlung der Brechungsexponenten der Mineralien im Dünnschliff durch Vergleich mit Canadabalsam und Kollolith," *Centralbl. f. Min.*, etc., (1921), 102–12.

The refractive index of Canada balsam in certain slides was found to be lower than the recently accepted values, being less than 1.5243. A series of experiments with Kollolith showed that the refractive index depended upon the original solvent and upon the temperature of heating. With hard kollolith and a temperature of 150° to 156°, the resulting mount was found to have practically a constant value of 1.5335, but with kollolith dissolved in xylol exposed to air, or under cover-glasses, the values varied from 1.519 to 1.5343, though the first averaged values between 1.5231 to 1.5343 and the latter 1.5257 to 1.5298, depending upon the time of exposure to the air, the higher values being obtained after about six weeks.

LYNES, HUBERT, AND SMITH, W. CAMPBELL. "Preliminary Note on the Rocks of Darfur." *Geol. Mag.*, LVIII (1921), 206–15.

The author describes rocks from the volcano of Dereiba and from various other points between there and El Obeid, Africa. None from this area has previously been described. Troctolite, granite, graphic granite, sandstones, gneisses, and quartz-monzonite occur on the road. The rocks of the volcano are quartz-bearing soda-trachyte, soda-trachyte, quartz-bearing riebeckite-trachyte, andesine-bearing kenyte, and mugearite.

MÄKINEN, EERO. "Översikt av de Prekambriska Bildningarna i Mellersta Österbotten i Finland," *Bull. Comm. Geol. Finlande*, No. 47, 1916. Pp. 152, map 1, figs. 25.

The pre-Bothnian rocks of the district described are represented by two small areas of ortho-gneisses. The Bothnian complex consists of plagioclase-

gneiss, mica-schist, conglomerate-gneiss, quartzite, and limestone, with some leptites. All but the latter are of sedimentary origin. Even the plagioclase-gneiss, which in chemical composition approaches certain igneous rocks, is sedimentary. The rocks have been formed, to a considerable extent, of unweathered volcanic material (volcanic ashes, as well as mechanically disintegrated materials from tuffs and lava beds) partly assorted and deposited in water. Associated with these rocks are certain intrusives and extrusives, mainly plagioclase-porphyrites, uralite-porphyrites, and amphibolites. The post-Bothnian rocks form a comagmatic series, chiefly abyssal but in part hypabyssal in character. The rocks are granite, syenite, granodiorite, quartz-diorite, diorite, gabbro, diabase, hornblendite, and peridotite. In the southwestern part of the area there were apparently two periods of intrusion from a magma differentiated *in situ*. In the parish of Haapavesi to Kivijärvi, there is no evidence of two periods of intrusion but the rocks, from granite to granodiorite and gabbro, grade into each other. The northern and eastern part of the area is an area of migmatites. Here the magma has been differentiated to a certain extent, but the different rocks have not been separated to form large homogeneous masses. The older rocks have undergone fairly complete assimilation by the magma. In the reviewer's modified classification the ortho-gneiss is 227′ (a granodiorite-gneiss), the plagioclase-porphyrite is 228 (quartz-diorite porphyry or tonalite-porphyry), four granodiorites are all 227′ (granodiorites in the broad sense, but quartz-monzonites if this group is included in the classification), twelve microcline-quartz-diorites are 227′ (monzotonalites narrow, or granodiorites in the broad sense), three tonalites are 228 (tonalite), a tonalite-gneiss is 227′ (monzotonalite-gneiss), three quartz-diorites are 228 (tonalite), a quartz-diorite is 328 (mela-tonalite), a diorite is 227′ (monzotonalite), two biotite-granites are 227″ (adamellites in the narrow, or granodiorites in the broad sense), an olivine-gabbro is 2312, and two soda-syenites are 2111′ (an albite-monzodiorite in the narrow, or albite-syenodiorite in the broad sense. The latter is the rock to which Laitakari compares his albite-epidote rock which he calls helsinkite. Laitakari's rock is given above in the reviews as 2112, from definition, but he says it may in some cases have a little microcline. The present rocks contain enough microcline,one 11 and one 7 per cent, to throw them into the next family.)

REVIEWS

Preliminary Report on the Deposits of Manganese Ore in the Batesville District, Arkansas. By HUGH D. MISER. Bulletin 715-G, United States Geological Survey, Government Printing Office, Washington, D.C., 1920. Pp. 93–124 (32), pls. 3, figs. 4, bibliography, tables, and analyses.

The Batesville manganese district is in the southern part of the Ozark region, in Independence, Sharp, Izard, and Stone counties, in north-central Arkansas. The deposits have been worked intermittently since 1849. They lie in a region of rough topography but of no great relief. In the manganese-bearing areas the following formations are exposed:

Age	Formation
Mississippian	Boone shert
Ordovician	Cason shale Fernvale limestone Kimmswick limestone Plattin limestone Joachim limestone St. Peter sandstone

The Cherty Fernvale limestone is the principal source of manganese ore. Its weathering leaves cherty nodules and sticky residual clay, varying in color from yellow to red. The overlying thin Cason shale bears phosphate, here as pebbles almost an inch in diameter, there as shell fragments or grains; such phosphate deposits have, however, not been extensively worked. The only fossils in the formation are flattened "buttons" of supposedly algal origin, composed of calcium or manganese carbonates; the "buttons" may occur in great quantity in the residual clay, as at the Cason mine.

Structurally the beds are almost flat-lying; a general doming of the region has given them a gentle dip southward, upon which are superimposed several minor flexures. There are seven small normal faults, with a throw not exceeding 400 feet. An uncomformity separates Mississippian and Ordovician beds and four others occur in the Ordovician sequence.

The manganese minerals are psilomelane, hausmannite, braunite, manganite, pyrolusite; and wad. Psilomelane is most abundant. Iron oxides (limonite and hematite), and ferruginous manganese ores (hematite and limonite with psilomelane), barite, quartz, calcite, arsenopyrite, and sulphides of the heavy metals are also associated with the ores. The workable manganese and ferruginous manganese deposits occur under the following conditions: (1) replacement deposits in the Cason shale and its residual clay; (2) replacement deposits in the Fernvale limestone; (3) residual deposits from the Fernvale limestone; (4) replacement deposits in clays; (5) transported stream-gravel deposits. Of these, (3) is most important as a source of manganese ores, and (1) has furnished more ferruginous manganese. The replacement deposits in the Cason shale and its residuum occur in irregular masses, "buttons," or horizontal seams and beds; "buttons" of red iron oxide are also found under similar conditions. The occurrence of manganese-bearing calcite suggests that all the manganese oxides were derived from the carbonate. A similar origin for the manganese replacements in the Fernvale limestone is well demonstrated by deep cuttings in the district: here cores of carbonate are found surrounded by envelopes of oxides of manganese and ferruginous manganese.

The largest yield of manganese ore, the largest reserves, and a considerable part of the low-grade ore output comes from the residual deposits of the Fernvale or lower limestones, into the deeper portions of which the nodules were settled by gravity or were washed by streams. The decomposition of the limestone has formed manganese-bearing surface hollows and channels; elsewhere manganese-bearing caves and sinks have developed. Slumping and sinking of the soft, plastic clay (and of the overlying Cason shale) have greatly disturbed the ore bodies. These residual deposits consist of psilomelane, hausmannite, wad, and, subordinately, braunite. The hard oxides may occur as bowlders that weigh as much as 22 tons; generally the coarser the masses, the more free the ore from iron and the higher its grade.

Some small deposits of manganese oxides have been formed by the introduction of manganese into the clays through the action of ground waters; such manganese probably came from the Cason shale or Fernvale limestone. These ores are low grade and diluted though the presence of silica, iron, and alumina.

Finally some manganese is obtained from alluvial cones and gravel bars, the deposits being composed of compact masses of manganese oxides, and of small pebbles of oxide of iron. Many of the largest concentrations

lie in synclines, for reasons which the writer hopes to demonstrate in a later paper.

Most of the high-grade ores bear from 45 to 52 per cent of manganese, but many otherwise good deposits bear too much phosphorous to justify exploiting them. "Hand-picked" ore is the highest grade. The ore is not used for chemical purposes, but is employed in various high-manganese iron and steel products; it is also of importance in making brown, gray, and speckled bricks, when mixed with clay.

The manganese reserves probably amount to 250,000 tons of 40 per cent manganese. The deposits are covered to the south by younger formations, and could probably not be extensively worked in that direction anyway, since concentration and oxidation have not been extensive under the heavy capping.

C. H. B., Jr.

Magnesite Deposits of Grenville District, Argenteuil County, Quebec. By M. E. Wilson. Memoir 98, Canadian Geological Survey, Ottawa, 1917. Pp. 88, figs. 2, pls. 11, maps 3.

This district is bordered by the Ottawa River on the south and is about halfway between Ottawa and Montreal. The magnesite deposits are about ten miles north of the Ottawa River.

Chapter i gives information of general interest about magnesite, its uses, foreign source of supply, other Canadian magnesite deposits, and the history of magnesite mining in Grenville district.

Chapter ii is a brief statement of the geology of the district. The oldest rocks belong to the Grenville sedimentary series and are intruded by pyroxene-rich gabbro, diorite, and syenite belonging to the Buckingham series. These two series are intruded by batholithic masses of granite-syenite gneiss. All these rocks are intensely metamorphosed and are Early pre-Cambrian in age. These Early pre-Cambrian rocks are intruded by diabase dikes and a stocklike mass of granite-syenite probably of Late pre-Cambrian age. The Paleozoic is represented by the Potsdam, Beekmantoan and Chazy formations named in ascending order. Glacial bowlder clay and gravel and Champlain marine clay form an irregular mantle over the bed-rock surface.

Chapter iii gives a description of the magnesite deposits and their origin. The magnesite is associated with serpentine, dolomite and other minerals in the metamorphosed Grenville sediments and close to outcrops of the pyroxenic rocks of the Buckingham series. The deposits are lens-shaped and the material is banded, the banding being due to

differences in color of the magnesite or from variations of amounts of serpentine and other minerals present. The strike of the bands and lenses is parallel to that of the Grenville sediments. The deposits have been intensely faulted and crumpled and probably the lenticular structure is the result of deformation. The mode of occurrence of the following minerals associated with the deposits is described: magnesite, serpentine, dolomite, diopside, phlogopite, quartz, talc, pyrite, sphalerite, magnetite, and graphite.

The three methods of origin for magnesite deposits are: (1) deposits formed by the decomposition of serpentine, (2) sedimentary deposits, (3) deposits formed by the replacement of limestone. The Grenville deposits are thought to have been formed by the replacement of limestone. Silication of limestone to diopside and phlogopite is very common along the contacts of limestone and igneous rocks in this region and the igneous rocks are very close to these particular deposits. The writer summarizes the method of origin: "The probable order of events by which the magnesite deposits of the Grenville district were formed was as follows: (1) silication of the limestone to diopside and the formation of phlogopite in places, (2) formation of serpentine in places, (3) replacement of limestone by dolomite, (4) replacement of dolomite by magnesite, and (5) the alteration of diopside to serpentine."

Chapter iv is a detailed description of the properties and gives tabulated descriptions of many magnesite samples with the percentage of CaO. While dolomite and magnesite are very intimately intermingled, yet by 1916 development work had proved the presence of 686,900 tons of magnesite containing less than 12 per cent CaO and 483,700 tons containing over 12 per cent CaO.

Map 1680 issued in 1919 shows in detail the geology of a portion of the township surrounding the deposits.

J. F. W.

Pleistocene Marine Submergence of the Hudson, Champlain and St. Lawrence Valleys. By HERMAN L. FAIRCHILD. New York State Museum Bulletins, Nos. 209, 210, Albany, N.Y., 1919. Pp. 76, pls. 25.

This is the closing paper by Professor Fairchild on the glacial and post-glacial waters of New York State and in it he discusses the proof and extent of the marine submergence following the retreat of Wisconsin glacial ice from northern New York State. The stratified clay and

sand in these valleys, the cobble bars, the wave-cut terraces, the deltas, and many other evidences of high-level standing water, with no known barriers to hold this water in, is strong evidence that the land in this region once stood below sea-level. This marine shore line has been uplifted and tilted and is now less than 100 feet above sea-level a short distance north of New York City and 740 feet above sea-level at Covey Hill on the International boundary, a distance of about 350 miles. Diagrams are given to show the profile of this tilted marine shore line and also the shore line of Lake Iroquois, the last of the glacial lakes to occupy the Ontario basin. In the St. Lawrence-Ontario basin the Iroquois plane is 290 feet above the marine plane and thus when one is found in the field it is easy to locate the position of the other. Also knowing the present elevation of these two planes and the total amount of uplift of the region, the amount of either glacial or post-glacial uplift can easily be determined. From numerous measurements and calculations of this sort it appears that northern New York State was not raised as a rigid body but by a progressive wave movement, as the southern side of Iroquois basin received one-half its total uplift during Iroquois time while the northern end of the same basin received very little uplift until after Iroquois time. The uplift of the land seems to have been wavelike and to have followed the margin of the retreating ice front.

Detailed descriptions of shore features in the various sheets along the Hudson, Champlain, and St. Lawrence valleys and the Ontario basin are given. The shore features at Covey Hill, the point of junction of the Champlain and St. Lawrence valleys and of the Champlain marine waters and the Lake Iroquois waters, are described in detail. Some of these shore features are at present somewhat above what the level of the water should have been at these particular localities. Many complications probably enter the Pleistocene history as there may have been many up-and-down land movements and the present height of the summit plane above the sea must represent only the excess of land uplift over the rise of the ocean surface and the arithmetical sum of all the up-and-down movements.

A large number of photographs are inserted to show summit shore features and at the end of the report a classified bibliography is given. This report summarizes in a very thorough and clear manner Professor Fairchild's interpretation of the various glacial and post-glacial deposits and physiographic features of this region.

J. F. W.

Iron Depositing Bacteria and Their Geological Relations. By EDMUND CECIL HARDER. United States Geological Survey, Professional Paper 113, 1919, Government Printing Office, Washington. Pp. 85, pls. 12, figs. 13.

Geology, probably more than any other science, occupies an apical position in the pyramid of the natural sciences; its function is not so much to enunciate the more fundamental theories *not* based on the concepts of other branches of knowledge, as to weld together the contributions of its sister-sciences and apply them to its own purposes. From this point of view a work such as that under review is especially illuminating; it demonstrates conclusively the hitherto only partially appreciated breadth of scope of the "science of rocks and minerals."

The paper begins with a careful description of the living iron-depositing bacteria, both those of the higher and those of the lower type. Not only the more common forms, such as Leptothrix, Galionella, and Spirophyllum are mentioned, but a brief review of the classification, morphology, and physiology of essentially all relevant forms known to date is given. The iron-bearing algae also are named. From the early work of Cohn and Zopf, who thought iron accumulation in bacterial sheaths essentially a mechanical process, through that of James Campbell Brown, who considered the deposition of ferric hydroxide to be merely incidental to the extraction of the organic constituents in the water affected, to the studies of Lieske, which demonstrated conclusively that the carbonate radicle of ferrous carbonate is extracted by the bacteria, leaving the insoluble hydroxide, the increasing importance of bacterial metabolism has come to be recognized. It is probable, in fact, that some bacteria require ferrous bicarbonate; that others can use it interchangeably with other soluble iron compounds; while still others, notably the lower groups, can use only the organic salts of iron.

Mr. Harder himself prepared and studied cultures of various forms. Crenothrix was obtained from city water of Madison, Wisconsin, which contained large amounts of magnesium and calcium carbonates. Cultures of Leptothrix ochracea were grown from the water of a chalybeate spring near Madison, the water bearing much ferrous iron in solution, probably as the bicarbonate; this form was also brought up from a low level of a Cuyuna District mine, where ferric hydroxide is being precipitated in large amounts. Cultures of Galionella ferruginea from the Federal Mine of Wisconsin and from the Kennedy Mine of central Minnesota are also reported; in both of these localities a brown, gelatinous scum occurs on the walls of the tunnels and in little pools in the drift-floors. Spirophyllum ferrugineum appears in the waters of the

Wisconsin zinc mines; it was also found in other mine-waters, probably being carried downward by surface waters that descended through the soil and rock for many hundreds of feet. The form is especially abundant in the water of Vermilion Lake, Soudan, Minnesota. All these bacteria precipitated ferric hydroxide.

Besides these there are other iron bacteria which precipitate ferric hydroxide or ferrous sulphide. The former group is especially widespread, and though its members do not require iron in solution for their development, still it is thrown down quite rapidly as a waste product. The precipitating action of such forms was studied by means of weak solutions of the slightly acid ferrous ammonium sulphate.

Whereas some of the sulphide-precipitating bacteria owe this ability to the action of the hydrogen sulphide liberated by them on the ferric salt in solution, others precipitate the sulphide because of their reducing action on the sulphate. When water bearing ferric ammonium citrate was inoculated with hay and soil infusions, there resulted a precipitation of ferric hydroxide not observed in the sterile solution. This ensues even under anerobic conditions. The organisms that induced it were grown on plates of Heyden Naehrstoff agar with ferric ammonium citrate as indicator and various types of bacteria were recognized. Slopes of Heyden agar to which no citrate was added showed practically no growth. Other organic salts of iron were also used more or less successfully, and similar experiments showed that no precipitations resulted from the solutions bearing salts of manganese in place of iron.

On the other hand, no precipitation that could be definitely assigned to organic processes could be obtained from inorganic iron salts such as the bivalent carbonate or sulphate or ferric chloride, the precipitation that *did* result in these cases being better attributed to the purely inorganic oxidation and (or) hydrolysis. These results do not agree with those of Mumford (*Chem. Soc. Jour.*, Vol. 103, 1913).

A review of the earlier work of Beijerinck, Van Delden, and Fred on the formation of hydrogen sulphide by bacteria may be summarized as follows: sulphates are formed abundantly by sulphur bacteria from hydrogen sulphide; these sulphates are then reduced by other bacteria to yield sulphides and hydrogen sulphide; if ferrous or manganese sulphides are formed they are precipitated. These observations have been ably and fully discussed in other papers, notably in their bearing on the origin of the Sicilian sulphur deposits.

The relations of these facts to geologic processes are amplified by the writer. He points out the solubility of iron carbonate; soluble organic compounds, chiefly humides, of iron may also be formed; it is

these that lend the dark color to streams flowing through regions of abundant vegetation. Finally, a smaller amount of iron may be carried as sulphate.

Iron deposits occur in the form of hydroxides and oxides, carbonates, and silicates. Iron is readily precipitated as the hydroxide, when a solution containing an excess of carbon dioxide is induced, through changes in pressure or temperature, to give up its gas with a concomitant saturation with oxygen; if the solution merely loses its carbon dioxide without undue oxidation, ferrous carbonate tends to be precipitated. These several iron precipitates generally accumulate in bogs, lakes, or lagoons. Elsewhere rapidly flowing waters may (rarely) form iron deposits.

Most deposits of bedded hematite, bog ore, and brown iron ore were laid down originally as hydroxides, chiefly through biologic, but also in part through chemical, agencies. Iron sulphide, too, may be formed in either way, but ferrous carbonates and silicates are not definitely traceable to bacterial action. Iron phosphates and basic ferric sulphates are chemical precipitates. Ferrous silicates tend to be deposited where alkaline silicates are abundant in regions of precipitation of ferrous carbonates—formed as indicated above. Probably 90 per cent of all the iron ores being worked today are of the sedimentary type. A list and description of those thought to be originally laid down as ferric hydroxide includes the Clinton ores, the Wabana ores, the Lake Superior hematite-chamosites, the itabirites of Minas Garaes, (Brazil) the hematite-magnetites of the Dharwar terrain of India, and the ores of the Norwegian Lias. Bog iron ores, too, were probably deposited in the same form and are now widely distributed, being especially abundant in the eastern part of Canada and the United States, in Sweden, and in the glaciated sections of Europe and Asia; ferric hydroxide is also present in large amounts in the red mud off the coast of Brazil.

Another type of sedimentary iron ore is that originally deposited as the carbonate; this is represented by the "black band" ores in Ohio, Pennsylvania, and West Virginia, the oölitic siderites of eastern England, and the siderites of the Lake Superior region.

The silicates present a third type of sedimentary iron ore. The forms in which the iron occurs include glauconite, bavalite, thueringite, bertherine, and chamosite; of these glauconite is the most widespread. Greenalite was probably the original constituent of the Mesabi ores, while the chamosite ores are predominant in the Bohemian Brdagebirge.

Ferric and ferrous sulphides represent the fourth type of iron deposits. Pyrite is important in the Huelva region of southern Spain, in the

Carpathian and Harz Mountains, and in Westphalia; the sedimentary origin of some of these beds, however, is still in doubt; more typically sedimentary are some of the oölitic pyrite beds of Wabana. Ferrous sulphide is common in the limans of the Black Sea. The general explanation offered for these deposits is that of Doss, who believed that the iron is carried as a carbonate, upon which bacteria may act directly or indirectly to yield colloidal ferrous sulphide or ferric hydroxide, which in turn is converted into ferrous sulphide.

Various facts of importance to students of sedimentation are brought out in a discussion of the origin of the separate iron deposits; for instance, the experiments by Spring and Ruff on the conditions favoring and opposing the derivation of limonite from ferric hydroxide. It is shown, also, that primary deposits of ferric hydroxide may be readily altered to the carbonate, especially in the presence of large amounts of organic matter.

From a discussion of the inorganic causes for the precipitation of iron compounds as sediments, the writer returns to a consideration of organic causes. Here, especially in connection with the precipitation of ferric hydroxides, the line is not readily drawn between oxidation, taken as the purely inorganic process, and bacterial action; the latter, however, is surely of much importance, whether actually preponderant or not. The conditions under which iron-bearing bacteria are active vary between wide limits. Temperature, if too high or too low, may be inhibitory, as may also be a reduction in the amount of organic matter present.

To present in detail all the significant facts of this interesting paper, would necessitate a review as long as the original publication; it must be read to be fully appreciated. It displays both the clear thought and the technical skill of Mr. Harder in original work and his ability to join his observations to those of other investigators of the subject. All in all, it is a most admirable contribution to experimental geology.

C. H. B., Jr.

Helium-Bearing Natural Gas. By G. Sherburne Rogers. United States Geological Survey, Professional Paper 121. Washington, 1921.

This report comes from the press many months after the accidental death of its author in South America. It reflects so zealous a spirit of scientific research in the public service that it stirs anew the sorrow of

his former associates at the passing of a geologist of such brilliancy and promise. The report perpetuates one of Mr. Rogers' contributions to the war needs of his country, namely the investigation of the occurrences of helium-bearing natural gas in the United States with a view to its utilization in dirigibles and military balloons.

Helium differs from hydrogen, the gas commonly used in balloons, in being non-inflammable; on the other hand it is about twice as heavy as hydrogen though still so much lighter than air that its lifting-power in air is 93 per cent that of hydrogen. Its advantages are so great that its use, both commercial and military, in airships is likely to be limited solely by the supply of helium available and the expense at which it can be produced.

The main body of this report is devoted to a description of the field occurrence of natural gases containing helium within the limits of the United States, but a brief discussion of possible sources of helium in other countries is included, and the report summarizes also, in very concrete and admirable fashion, the history of helium, its properties, and its relations to the radioactive elements, as well as the methods which have been applied for separating it from the commoner constituents of natural gases. The field work upon which the investigation rests consisted chiefly in collecting samples of gas for analysis and in gathering data regarding depth, geologic position, rock pressure, and volume of the gas sampled. This work involved careful examination of the geological structure in one or two areas, though a number of helium-rich districts had been previously studied by Survey geologists, and data on others were furnished by oil companies.

As a result of the investigations it is shown that although most of the natural gas produced in the eastern and central parts of the United States contains at least a trace of helium, gas containing more than $\frac{1}{2}$ per cent is known to occur only in two areas, one in northern Texas and the other in southern Kansas and northern Oklahoma. The helium-rich gas of the Kansas-Oklahoma area is confined to strata of Middle and Upper Pennsylvanian age, though gas carrying almost $\frac{1}{3}$ per cent of helium occurs in the Lower Pennsylvanian. The Mississippian and Permian gases in that locality are poor in helium. Conditions in the Texas area are almost identical. In Ohio gas carrying $\frac{1}{3}$ per cent of helium occurs in the Lower Mississippian and in the Clinton of the Silurian. Nearly all samples of Cretaceous gas from various parts of the United States show only traces of helium and most samples of Tertiary gas contain none.

Although traces of helium occur in most natural gas, noteworthy proportions have been found only in gas rich in nitrogen. The percentage in helium, moreover, seems to depend, in a measure, on the percentage of nitrogen, though there is not direct proportionality between the two. Some of the Kansas gases contain about 85 per cent of nitrogen and 2 per cent of helium.

After a discussion of the occurrence of helium in minerals and rocks, in mine gases and in the gases of mineral springs, volcanoes and fumeroles, the theories that have been advanced in explanation of the origin of the helium in natural gases are discussed. While recognizing that the origin of the helium is still a matter of great uncertainty, the writer is inclined to favor the view that the helium is derived from deposits of uranium and thorium, probably disseminated through the strata not far beneath the horizons at which the helium gas occurs.

E. S. Bastin

The Economic Aspects of Geology. By C. K. Leith. New York: Henry Holt and Company, 1921.

Because each year modern industry is becoming more technical, industrial progress has come to stride pace after pace with the development of science. Geology has shared with other sciences in the tightening of the bonds between science and industry. It is no longer necessary, as it was a generation ago, for the geologist to be continually bringing before the public the practical potentialities of his science; certain industries are now even snatching the half-fledged geologists from their academic nests. The increasing industrial importance of geology lays a new responsibility upon those engaged in the training of economic geologists, and Professor Leith's book, an embodiment of lectures given at the University of Wisconsin, drives home to the geology student in vigorous fashion not only the fundamental facts of useful mineral occurrence but also the rôle which each of these minerals plays in the economic life of the nation and of the world. The book is, in fact, an outgrowth of its author's war-time experiences during which he distinguished himself as a leader in the first real inventory of her mineral resources that the United States had ever taken.

The work is adapted to the use of students having an elementary knowledge of geology, such, for example, as is commonly acquired in the first year's work in college geology. While adapted for the use of

students, most mining engineers and teachers of geology will find that it gives them not only a new array of facts, but a broadened viewpoint.

After introductory material, a chapter is devoted to the common elements, minerals and rocks of the earth and their origin, and another chapter to a simple exposition of the processes by which mineral deposits are formed.

In the consideration of individual mineral resources, the conventional classification as metallic and non-metallic is abandoned in favor of one that is more expressive of their rôle in industrial life. Early in the scheme come the fertilizer group of minerals, nitrates, potash, phosphates, pyrite, and sulphur. Then come the fundamental fuels, coal, oil, and gas. In the same chapter with iron and steel are treated the ferro-alloying minerals and the minerals fluorite, magnesite, and silica, that find their main use as fluxes or refractories in the iron and steel industry. Other major base metals are followed by the precious metals, and then by minor metals. The commodity chapters are concluded with one devoted to miscellaneous non-metallic minerals.

A feature of the treatment of individual commodities that makes for clarity is the treatment of "Economic Features" and "Geologic Features" under separate heads.

Conservation of mineral resources, particularly coal, comes in for separate treatment in a chapter near the end of the volume. Especially noteworthy are several topics that have received scant treatment, if any, in previous books on economic geology; namely, exploration and development of mineral deposits, the rôle of the geologist in their valuation and taxation, and a brief discussion of the legal aspects of geology.

The book concludes with chapters summarizing the international aspects of mineral resources, on "Geology at the Front" and "Geology Behind the Front."

The field occupied by this book is covered by no other, and few books are likely to fill as useful a place in geologic education.

EDSON S. BASTIN

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THE BEHAVIOR OF INCLUSIONS IN IGNEOUS MAGMAS

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INTRODUCTION

Many igneous rocks contain inclusions of foreign material and not infrequently these inclusions show evidence of having been attacked by the magma, some to a moderate extent and others to such an extent that only traces of the inclusion remain. To some petrologists these inclusions are but the remnant of a great host, most of which has been completely incorporated in the magma, and to such incorporation or assimilation of foreign matter they would assign the principal variations of igneous rocks. The variations are not usually regarded by these petrologists as the result of assimilation alone but of assimilation followed by the differentiation of the syntectic magma which is supposed to have special powers of differentiation not possessed by the original magma. Other petrologists believe that magmas cannot be expected to have the energy content necessary for the solution of a significant amount of foreign material; that the amount of solution actually observed at and near contacts is an approximate measure of the total and that the variations of igneous rocks are quite independent of these slight additions, being due to spontaneous powers of differentiation possessed by original, uncontaminated magmas.

In the present paper it is proposed to discuss the behavior of inclusions with special reference to these questions. By application of the principle of the reaction series, as developed in a former paper,[1] it is hoped to effect a certain amount of reconciliation of these extreme views.

HEAT EFFECTS OF SOLUTION

Since one of the important questions involved is that relating to the heat effects resulting from solution it is desirable to consider the information available on these effects. The ordinary equilibrium diagram, commonly regarded as a freezing-point diagram, is at the same time a solubility diagram. It gives the change of solubility of any phase with temperature. But the change of solubility with temperature depends mainly[2] on the heat effect involved in solution and the equilibrium diagram contains complete information on this heat effect. Unfortunately the information may be very difficult of extraction; in the present state of knowledge, often impossible. One solubility diagram, that of the plagioclase feldspars, has proved particularly simple in this respect. This diagram is shown in Figure 1, the curves being calculated on the basis of a latent heat of 104.2 cal. per gram for anorthite and 48.5 cal. per gram for albite. The determined points are given by the small circles and their correspondence with the calculated curves is very remarkable. Since the curves were calculated on the basis of constant latent heats (solution heats) this correspondence simply means that

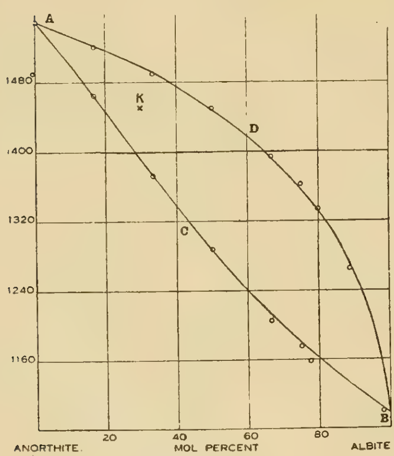


FIG. 1.—Equilibrium diagram of the plagioclase feldspars. The circles indicate determined points. *ACB* and *ADB* are calculated curves assuming no heat of mixing.

[1] N. L. Bowen, *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

[2] The volume change is involved also but is relatively unimportant.

there are no mixing-heat effects and that the heat of solution of any plagioclase in liquid plagioclase is simply the latent heat involved in the change from solid to liquid.[1]

In Figure 2 is plotted the equilibrium diagram for anorthite and diopside. Now we know the latent heat of anorthite from the calculated results of Figure 1 and we may calculate, using this value, a

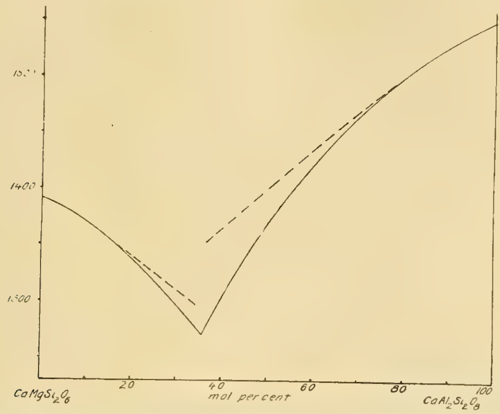


FIG. 2.—Equilibrium diagram of diopside and anorthite. Determined curves in full lines. Broken curves calculated on the assumption of no mixing heats.

curve of freezing-point depression for anorthite according to the equation for ideal concentrated solutions, viz.:

$$T=\frac{T_0}{1-\frac{2T_0}{Q}\ln x}$$

where T is the melting temperature (saturation temperature) of anorthite in a solution of mol fraction x in anorthite; Q is the latent heat of melting per mol of anorthite (=29,000 cal.) and T_0 its melting-point (=1550°). As a result of this calculation we obtain the right-hand dotted curve. It will be noted that the determined curve corresponds with the calculated dotted curve in the upper portion (as far as about 80 per cent anorthite) and then falls below. In other words, we could have calculated the latent

[1] See N. L. Bowen, Melting phenomena of the plagioclase feldspars. *Amer. Jour. Sci.*, Vol. XXXV (1913), p. 590.

heat of anorthite from a point on the upper portion of the determined curve. If now we do this for the diopside curve, that is, calculate the latent heat of diopside from a point on the upper portion of its solubility curve, we find a latent heat of 23,420 cal. per mol or 108 cal. per gram.[1] Calculating the further course of the curve with the use of this value we obtain the dotted curve. This calculated curve also lies above the determined curve at points distant from pure diopside. There is one factor which can cause such a deviation of the freezing-point curve from the theoretical curve of the above equation, viz., a heat of mixing of the liquids, and Van Laar has developed an equation which enables one to calculate the differential heats of mixing involved. The equation is

$$T=T_0\,\frac{1+\dfrac{a(1-x)^2}{[1+r(1-x)]^2}}{1-\dfrac{2T_0}{Q}\,lnx}$$

where a and r are coefficients from the Van der Waals equation of state for binary mixtures. The numerator gives the number of times the solution heat, at the concentration x and temperature T, is greater than the melting heat Q, and the difference between this and Q is the differential heat of mixing.[2] From this equation we find the following values of the differential heats of mixing per mol (q).

TABLE I

MOLAL DIFFERENTIAL HEATS OF MIXING IN ANORTHITE-DIOPSIDE MIXTURES

For anorthite	x..........	0.8	0.5	0.4	0.35
	q (cals.).....	100	600	1100	1250
For diopside	x..........	0.7	0.65	....	....
	q (cals.).....	120	340	....	....

Now these differential heats of mixing are the heats of mixing of one mol of liquid with a very large amount of solution of the various concentrations referred to. These in themselves have no particular

[1] A direct determination by W. P. White gave 106±15 cal. *Amer. Jour. Sci.*, Vol. XXVIII (1909), p. 486.

[2] *Z. physik. Chem.*, Vol. VIII (1891), p. 188.

interest from the present point of view but from them the so-called integral heats can be calculated by a graphical method. Roozeboom[1] shows that if the curve of integral heats of mixing is plotted against mol fractions of the components then the intercept on the heat axis of the tangent to the curve gives the differential heat of mixing for the composition represented by the point. Thus in Figure 3 if the curve *ABC* represents the heats of mixing of diopside liquid and anorthite liquid in various proportions to form one mol of mixture, then the differential heat of mixing of one mol of

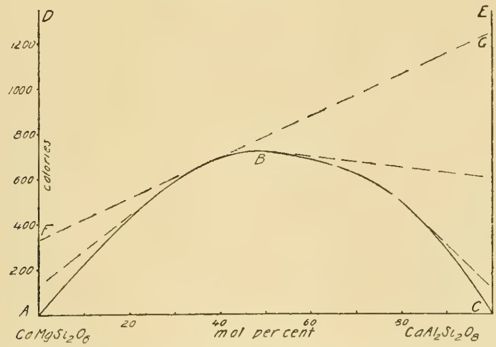


FIG. 3.—Curve of integral mixing heats of diopside and anorthite liquids (*ABC*). Showing graphical method of determining integral mixing heats from differential mixing heats.

anorthite in a large amount of liquid of the mol fraction x is given by the intercept on *CE* of the tangent at x. Also the differential heat of solution of diopside in this same mixture is given by the intercept on *AD* of the same tangent. Now in our particular case we have determined the differential heats by calculation from the freezing-point curves and we wish to know the integral heat. This is the reverse of the above problem and while not as straightforward can nevertheless be solved in the same way. We have, fortunately, for the composition of the eutectic, the differential heats of mixing for both diopside and anorthite which completely fixes the tangent at the composition of the eutectic. Figure 3, which has been referred to for purposes of illustration, is also the actual figure for diopside and anorthite determined graphically from

[1] *Die Heterogenen Gleichgewichte*, Zweiter Heft, Erster Teil (1904), pp. 287–90.

the calculated differential heats of Table I. Thus *FG* is the tangent at the composition of the eutectic joining the value of the differential heat of mixing for diopside liquid in the eutectic with the differential heat of mixing for anorthite liquid in the eutectic liquid. This fixes immediately that the integral heat of formation of one mol of the eutectic liquid from its liquid components is 650 cal. Knowing that the curve of integral heats is tangent to this line at $x=0.65$, we may readily draw a complete curve (the envelope of the family of tangents) that satisfies the known values of the differential heats. When this is done we get the curve *ABC*. This curve, then, gives us directly the amount of heat evolved when liquid anorthite and liquid diopside are mixed in any proportion. Thus when $\frac{1}{4}$ mol diopside liquid is mixed with $\frac{3}{4}$ mol anorthite liquid 500 calories are evolved. The maximum amount of heat per molecule of mixture (720 cal.) is evolved when about .047 mol of anorthite liquid is mixed with 0.53 mol of diopside. This happens to be about equal weights, so that the maximum amount of heat is evolved when about equal weights are mixed and is equal to about 3 cal. per gram of mixture. This heat is sufficient to heat the mixture about 10°.

If now we turn to the equilibrium diagram of diopside and albite and calculate a curve of freezing-point depression for diopside, using the value of the latent heat found from the anorthite diagram, we find again that the calculated curve coincides with the observed curve in its upper portion and then deviates from it (Fig. 4), but in this case in the opposite direction to that found for the other diagram. Again, this deviation can be interpreted as due to a heat of mixing of the liquid but now of the opposite sign. If we apply the Van Laar equation we can calculate the differential heats and from these determine graphically as before the integral heats of mixing. Thus we get Figure 5.

We find, then, that albite liquid and diopside liquid mix with absorption of heat, the maximum absorption (790 cal.) taking place when 0.48 mol albite is mixed with 0.52 mol diopside. This also is about equal to 3 cal. per gram of mixture.

Assuming that the theoretical basis of our calculations is to be relied upon we have proved that anorthite and diopside, both

characteristic molecules of basic rocks, mix in the liquid state with evolution of heat, whereas albite, one of the most characteristic molecules of acid rocks, mixes with diopside in the liquid state with absorption of heat and with anorthite without significant heat effect.

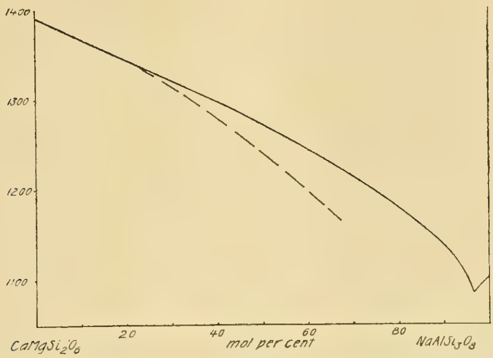


FIG. 4.—Equilibrium diagram of diopside and albite. Determined curves in full lines. Broken curve calculated on the assumption of no mixing heats.

These results are quite the opposite of what is often assumed to be the case. Many statements are to be found in the literature to the effect that acid and basic rock material will mix with evolution of heat. There is nothing in the results of studies of phase equilibrium

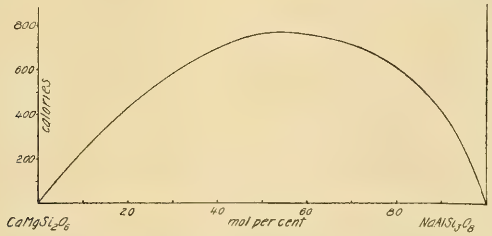


FIG. 5.—Curve of integral mixing heats of diopside and albite

to warrant such a statement; indeed, there are, as we have seen above, good reasons for doubting it.

Possibly in rare cases, where more fundamental reactions are involved, greater heats of mixing are available, but the mixing of two liquids has, in itself, little importance in petrogenesis. Our particular interest lies in the heat effect on mixing solid rock-matter

with liquid magma. In that connection, however, the heat of mixing of liquids is not without significance, for the heat of solution of a solid is to be regarded as the resultant of two heats, the heat of melting of the solid and the heat of mixing of the liquids. Now the heats of mixing that we have calculated above are really very insignificant as compared with the heats of melting of the solids, and the heats of solution of the solids are, therefore, very nearly equal to the latent heats of melting. For the solution of solid anorthite in diopside a little less than the latent heat is required, for the solution of solid albite in diopside a little more than the latent heat is required. The differences are noteworthy in connection with any theory that postulates an evolution of heat when an acid rock is immersed in basic magma, but for the purposes of the present inquiry which seeks to find merely the order of magnitude of the heat effect when solid rock is added to magma, we may state that the heat of solution of solid anorthite, albite, or diopside in any liquid mixture of them is substantially equal to the latent heat of melting. Moreover it is probably true of silicates in general that the solution of the solid is attended by a large absorption of heat, though not many determinations lend themselves to interpretation in the same way as the above. Thus when one attempts similar calculations from the equilibrium of anorthite with nephelite and of anorthite with silica it is found necessary to assume molecular association in nephelite and silica, and, while this is not surprising since both occur in more than one crystal form, it nevertheless so complicates the case that interpretation becomes impossible. One thing is certain, namely, that all the solubility curves of silicates yet determined show a marked increase of solubility with temperature, which means a strong absorption of heat upon solution. No example of retrograde solubility is known. In conclusion, then, we may state that the solution of a silicate in a magma is usually accompanied by a large absorption of heat, probably of the order of magnitude of the heat of melting.

THE QUESTION OF SUPERHEAT

Having thus arrived at a general conception of the heat required for solution we may consider the question of the heat available. One aspect of this is concerned with the superheat of the

magma, that is, the excess of temperature above that at which crystallization begins. Somewhere within the earth there is material (whether a rigid liquid or a crystalline solid we need not here consider) which is capable of becoming fluent liquid upon release of pressure. At great depths there may be excessively hot material capable of giving excessively hot liquid, but this is hardly concerned with matter that ever comes to the light of day as an igneous rock. There must be a transition zone representing a passage from stable crustal material incapable of becoming magma, through a zone capable of giving magma with some suspended crystalline matter, to a zone capable of giving a completely molten magma. It is from the zone giving rise to magma with some suspended crystals, rather than from the zone giving a simple liquid, that we must expect the great upwellings of magma to come, because of the advanced position of the partly crystalline material with respect to an action producing such upwelling and because it may be readily mobile when the amount of suspended crystals is small. As the magma rises in the crust several factors may combine to reduce the amount of crystals. Among these factors is the increased solubility of the crystals resulting from the lowered pressure, for the solution of silicates usually takes place with increase of volume. Besides this there may be an actual addition of heat as a result of the Joule-Thomson effect[1] and of possible exothermic reactions ensuant upon reduced pressure. It is probable that, in the usual case, the magma still retains some crystals even when it rises to shallow depths within the crust for, though the intensity of the above actions is thereby increased, it is also passing into colder and colder surroundings and must lose a corresponding amount of heat. It is possible that in some cases a magma may have lost all its crystals by the time it has risen to shallow depths and perhaps may have a temperature above the saturation temperature under the conditions there prevailing. However, even if we make the liberal assumption that it is superheated 100° (say its temperature is 1100° and the saturation temperature 1000°) and that this condition is acquired when it has reached a level 5 km. below the surface, it should be noted that the mere immersion of blocks of country rock amounting to about

[1] L. H. Adams, *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 144.

10 per cent of the mass of magma would be sufficient to wipe out this superheat, for the original temperature of blocks even at this quite considerable depth would be only 200°.

This, too, is quite apart from the amount of heat that must be lost by the magma in heating up a large amount of wall rock other than the immersed fragments. If we consider greater depths, where the surroundings would be at a higher temperature, it must be remembered that we are thereby limiting the amount of superheat that may have been acquired as a result of those processes attendant upon the rise of the magma and proportional in amount to the extent of rise.

It is plain that there can seldom be more than a very small amount of superheat left after the heating up of immersed fragments. Occasionally, perhaps, such small amounts may be available for the direct solution of fragments but it would require only an excessively small amount of solution to use up this heat, a fact that becomes apparent when the enormous discrepancy between the specific heats of silicate liquids (0.2–0.3 cal.) and the solution heats of silicates (50–125 cal.) is realized.

We have thus deduced, from general considerations, that magmas cannot be expected to have much superheat and in particular that they cannot retain a significant amount after the immersion of foreign fragments in such quantity that an important effect upon the composition of the magma would ensue if solution did occur. This deduction need not be regarded as contradictory to the observed fact that on very rare occasions inclusions of foreign rock have been found converted into glass by magmas and that the measured temperatures of lavas at certain active volcanoes are sometimes high enough to indicate a condition probably significantly above that of beginning of crystallization. It is becoming increasingly apparent that in central volcanoes there are sources of heat, probably from exothermic gas reactions, that are capable of producing the temperatures observed, but these must be regarded as locally concentrated where the gases have their vent. Moreover, inclusions converted to glass are found almost exclusively in such extrusive rocks. Even their rare appearance in intrusive masses need not militate against the general conclusion reached, for, admitting a

certain amount of superheat, the first few inclusions added would receive the full benefit of it and might be fused, but the magma would suffer a correspondingly marked loss of heat. In other words, the net result of the addition of an amount sufficient to produce a significant change of composition, say 10 per cent, would be the same even though they were added slowly and the first additions were drastically affected. Not only do magmas commonly fail to convert inclusions into liquid but they also fail to effect such changes as the transformation of quartz into tridymite and of wollastonite into pseudo-wollastonite, which fact must be regarded as indisputable evidence of the prevailing low temperatures.

There seems no reason, therefore, to doubt that direct solution of foreign material in superheated magmas cannot be a factor of importance in petrogenesis. However, the importance of superheat has been greatly exaggerated both by those who adhere to the view that magmas dissolve large quantities of foreign matter and by those who deny it. We shall find in the sequel that even saturated magmas may produce very marked effects in the way of incorporation of foreign material.

EQUILIBRIUM EFFECTS BETWEEN "INCLUSIONS" AND LIQUIDS IN INVESTIGATED SYSTEMS

In the following discussion of the effects of liquids upon inclusions, whose composition is embraced within investigated systems, attention will be confined, unless otherwise stated, to saturated liquids. This is done because we have found in the foregoing discussion that the superheated condition has little importance in nature. But lest it be thought that this is going too far in the way of eliminating superheat we have made another assumption that should amply compensate, namely, that the inclusions are already heated to the temperature of the liquid before immersion in it.

It is proposed to discuss the magnitude of the heat effects involved when reactions go on between solid inclusions and liquid in systems that have been experimentally investigated and where the equilibrium relations at various temperatures and the approximate heat effects are known. It is not expected that the numerical results so obtained will have any direct applicability to natural

magmas, but it is hoped that some principles of general significance may be thereby brought to light.

As a beginning we shall refer to equilibrium in the plagioclase feldspars which is given in Figure 1. In the figure we note that liquid of composition Ab_1An_1 begins to crystallize with the separation of crystals of composition about Ab_1An_4. As the cooling proceeds, if perfect equilibrium obtains, the crystals will be made over by the liquid so that the composition of the crystals changes along the curve *ACB*. It is plain, then, that if one had a mass of liquid Ab_1An_1 at 1450°, that is just saturated, and added to this mass some crystalline material of the composition Ab_1An_4 (approx.) (already heated to 1450°) which we shall now call foreign inclusions, the liquid would, if perfect equilibrium were attainable, make over these inclusions as the temperature fell so that their composition followed the curve *ACB*. How much of this work the liquid will be able to accomplish in any individual case will depend on such factors as the size of the inclusions, their permeability to the liquid, and the rate of cooling, but the tendency is very plain. We can thus have a liquid exerting a marked influence upon inclusions even though these are precisely of the composition in equilibrium with the liquid, provided the solid is a member of a solid solution series. It should be noted, however, that this action is without effect on the course of the liquid. The composition of the liquid follows the curve *ADB* whether the inclusions are present or not. The career of the liquid may, however, be brought sooner to a close as a result of reaction with the inclusions, that is, the liquid may be entirely used up at a somewhat higher temperature.

We may now examine the case of adding to a plagioclase liquid some solid plagioclase more calcic than that with which the liquid is in equilibrium. To 50 g. liquid Ab_1An_1 at 1450° (just saturated) let us add 50 g. solid Ab_1An_9, already heated to 1450°. Equilibrium will be established, if the temperature is kept constant, only when the solid is completely changed to that with which the liquid is in equilibrium, Ab_1An_4 (approx.). Since the total composition is represented by the point *K* we can easily determine the proportions of liquid and crystals. They will be 17 per cent liquid of composition Ab_1An_1 and 83 per cent plagioclase of composition Ab_1An_4

(approx.). We have now 66 g. An and 17 g. Ab in the crystalline state. We had formerly only 45 g. anorthite and 5 g. ablite. Equilibrium will therefore be established with evolution of heat to the amount of $21 \times 104.2 + 12 \times 48.5$ cal. In order to keep the temperature constant, then, we should have to abstract 2770 cal. If, on the other hand, no heat were abstracted the temperature would rise somewhat and equilibrium would be established at a slightly higher temperature. For the particular case we have assumed we may readily calculate that equilibrium would be established at about 1465°, when the mass would consist of about 60 per cent crystals of composition Ab_1An_5. Even when the reaction takes place adiabatically, there is an increase in the proportion of crystals. The reaction is in no sense a solution of foreign material. Rather by a making over of the foreign material it becomes no longer foreign but identical with the crystalline matter with which the liquid is in equilibrium. Moreover, if the originally foreign matter is more calcic than the crystals with which the liquid is in equilibrium the reaction is an exothermic one. How much of this reaction would take place in any individual case cannot be predicted. It will depend upon rate of cooling and other factors that readily suggest themselves, but there is plainly a tendency toward such a reaction and the reaction is exothermic.

Let us now examine somewhat more minutely into the cause of this exothermic reaction and we shall find that it is due to a general principle and is not dependent upon the particular properties of the plagioclase series discussed. During the crystallization of a plagioclase mixture a small decrement of temperature results in the reaction:

plagioclase+liquid=a little more plagioclase of somewhat more sodic composition.

Since this is an *equilibrium* reaction taking place with falling temperature, it must be exothermic. When we add the plagioclase Ab_1An_9 to liquid Ab_1An_1 we merely integrate this reaction over the temperature range 1500°–1450° and the composition range Ab_1An_9–Ab_1An_4. Thus we could start with a liquid of composition Ab_1An_5, permit it to crystallize until at 1500° the crystals would be of the composition Ab_1An_9, filter off the crystals, permit the liquid to cool to 1450°,

when it would attain the composition Ab_1An_1, and then add the foreign crystals Ab_1An_9 that we filtered off. It is plain that we would have available by the making over of these crystals at 1450° all the heat that would have been evolved between 1500° and 1450° by the continuous process of making over of these crystals had they been left in contact with the liquid. Though we have used the plagioclase series as an illustration it is clear that the exothermic reaction taking place at 1450° is merely a deferred result of the principle of Le Chatelier which states that an equilibrium reaction proceeds, with falling temperature, in the direction resulting in evolution of heat. It is a perfectly general property of any solid solution series that if, at any temperature, crystals which are at equilibrium with liquid at a higher temperature are added to saturated liquid, the reaction which ensues between liquid and crystals is exothermic.

The case of the addition of an inclusion of composition nearer the low temperature (more sodic) end of the solid solution series may now be examined. A liquid of composition Ab_1An_2 is just saturated at 1490°. We cannot add to it a more sodic solid inclusion at the same temperature because any more sodic inclusion will be liquid at this temperature. But if we add inclusions of Ab_2An_1 at such a temperature that they are solid, say 1200°, it is plain that the actual temperature of the liquid is adequate to melt these inclusions; the only question is the source of the quantity of heat. The liquid must, of course, be cooled off in supplying the heat required to heat up the inclusions, but, since the liquid is saturated, it cannot be cooled without some crystallization taking place. However, it will take a very small amount of crystallization to supply the heat necessary to heat up a considerable amount of inclusions. The enormous discrepancy between the specific heats of silicates and their solution heats is plainly of double significance in connection with these problems. Not only can the heat necessary to heat up the inclusions be supplied by crystallization of some of the liquid, but so also can the heat required to melt the inclusions. To accomplish this it will require, however, the formation of crystals approximately equal in amount to the amount of inclusions melted. If we added 20 per cent of inclusions of Ab_2An_1 at 1200°, to a liquid of composition Ab_1An_2 at 1490° we would obtain (assuming that these thermal

adjustments took place very rapidly compared with concentration adjustments) a mass of liquid about (Ab_2An_3) containing in it about 20 per cent of crystals of the kind in equilibrium with it (about Ab_1An_5) and containing also the inclusions converted to liquid, the whole at a temperature of about 1470°. There is no objection, therefore, to the conversion of an inclusion into liquid if the inclusion is sufficiently contrasted with the magma in composition in the proper direction; nor is such melting of an inclusion to be regarded as evidence of superheat in the magma.

This condition, in which liquid inclusions are contained in the magma, is of course a temporary one and it is rather the end result that has particular significance in petrogenesis. Final adjustment of concentration takes place by formation of a single homogeneous liquid and adjustment of the composition of the crystals to that in equilibrium with this liquid. This necessitates a further drop in temperature to about 1460° where the whole mass consists of the liquid $Ab_{45}An_{55}$ containing somewhat less than 20 per cent crystals of the composition about Ab_1An_4. Thus the net result of the addition of inclusions of composition more sodic than the liquid is that the inclusions become a part of the liquid and at the same time calcic crystals are formed in amount slightly less than the amount of inclusions added, the heat needed in order to make the inclusions part of the liquid being supplied by the formation of crystals. In the sense that they become a part of the liquid the inclusions are dissolved, but the process is not simply the formation of a liquid whose composition is the sum of that of the magma and the inclusions.

Let us now observe how these effects are carried over into more complex systems. Figure 6 is the equilibrium diagram of the system diopside: anorthite: albite for which we have discussed the heat quantities on an earlier page and found that the solution heat of any solid phase can be regarded as substantially equal to its latent heat of melting. A liquid of composition *A* is, at 1250°, just saturated with plagioclase of composition Ab_1An_4 approximately. If foreign inclusions consisting of the plagioclase Ab_1An_9 were added to this liquid we would have an effect strictly analogous to that described for simple plagioclase mixtures. The liquid would tend to make the inclusions over into Ab_1An_4 which takes place with evolution of heat.

If the rate of withdrawal of heat were very slow this reaction might result in an actual rise of temperature and the establishment of equilibrium at the higher temperature where the plagioclase crystals would be slightly more calcic than Ab_1An_4. If the liquid *A* had come into being as a result of the partial crystallization of another liquid, and if it carried plagioclase crystals suspended in it that showed zoning, the addition of the foreign inclusions mentioned might therefore result in a reversal of the zoning.

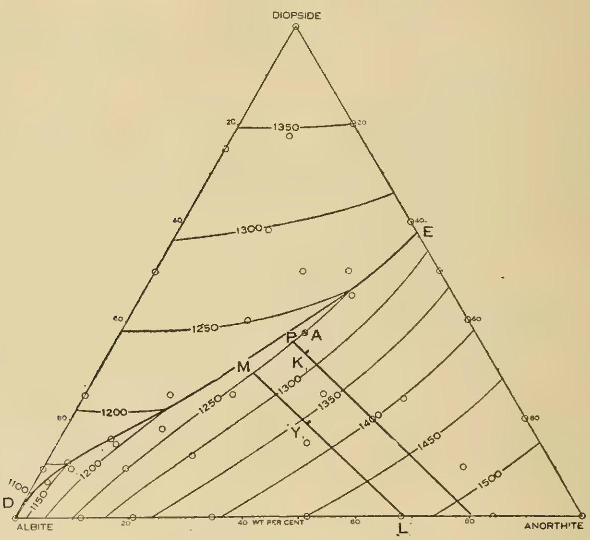


FIG. 6.—Equilibrium diagram of diopside, anorthite, and albite

The "attack" of the liquid upon the inclusions would be facilitated at the margins and along any channels where the inclusion happened to be more readily penetrated. The replacement of a small unit of Ab_1An_9 by Ab_1An_4 means a large local increase of volume so that the action is bound to have a disintegrating effect upon an inclusion suspended in liquid. Thus the material of the inclusion, as it is gradually made over, tends to become strewn about in the surrounding liquid but there is no actual solution, no increase in the amount of liquid—indeed, there is a diminution. Such should be the behavior of an inclusion richer in calcic plagioclase than the crystals with which the liquid was in equilibrium. At a later point

in the paper it will be shown that the observations of many petrographers upon actual rock inclusions strongly suggest just such an action.

If we turn now to inclusions of plagioclase less calcic than the crystals with which the liquid is in equilibrium we find that quite a different condition obtains. We may begin with the liquid *A*, again at 1250°, and add to it foreign inclusions of Ab_1An_1 already heated to 1250°. It will be noted that we are adding plagioclase of the same composition as that in the liquid since liquid *A* is a mixture of Ab_1An_1 and diopside. Suppose that the reaction takes place at first between a thin layer of liquid adjacent to the inclusion and an equal weight of the peripheral part of the inclusion. The composition of this reacting mass is then to be represented by the point *Y*. Suppose further that the reacting mass is a very small portion of the total so that no significant drop of temperature occurs, for in this case the reaction absorbs heat. Equilibrium will be established in this reacting layer sensibly at 1250° when the composition of the crystalline outer crust of the inclusion is Ab_3An_7 (*L*) and that of the adjacent thin layer of liquid is *M*, which is a mixture of Ab_2An_1 and diopside. If the general cooling of the liquid were proceeding rapidly so that this condition were "frozen-in" we would have a central core of unaltered inclusion of composition Ab_1An_1, an altered crust of the inclusion of composition Ab_3An_7, a reaction rim (formerly liquid) about this, consisting of a mixture of diopside and Ab_2An_1, all surrounded by the main mass consisting of a mixture of diopside and Ab_1An_1. The reaction rim is not intermediate in composition between the inclusion and the main mass, nor yet between the altered crust of the inclusion and the main mass. This is a commonly observed feature of reaction rims and has been referred to "selective diffusion," an explanation which is correct but rather misleading. The effect is really due to equilibrium effects between the inclusion and the liquid and such diffusion as occurs is selective only because equilibrium selects certain constituents to become part of the liquid and others to be fixed in the solid phase. In the case we have described, more sodic plagioclase is emphasized in the new liquid formed and more calcic plagioclase is emphasized in the solid product. We shall find it to be a general result of reactions of this

kind that the liquid should be enriched in the constituents toward the low temperature end of a solid solution series and the solid in those toward the high temperature end.

We have seen, then, that even when we add inclusions of a plagioclase of the same composition as the plagioclase existing as liquid in the magma, quite marked reaction effects may be found.

Let us now examine the same example but make the cooling of the liquid very slow. In other words, we shall discuss the end result of the action described above, which gives a reaction rim only as a temporary condition. In this case we shall imagine that the liquid formed about the inclusion becomes a part of the main mass of liquid as a result of diffusion and convection, and also that the solid products of the reaction become distributed through the liquid upon disintegration of the inclusion, due to the formation of local pockets of liquid and to the volume changes taking place in the change of composition of the solid phase. Thus the inclusion completely disappears as a distinct entity. Let us imagine that the amount of the inclusions was 10 per cent of the total and determine what the effect on the mass as a whole will be. The bulk composition of the mass is represented by the point K and if the temperature were maintained at 1250° the inclusions, formerly Ab_1An_1, would be changed to crystals of a composition close to Ab_1An_4 and the liquid would acquire the composition P. The crystals would amount to only about 6 per cent of the mass and to maintain the temperature constant would require addition of heat. If the only heat available were that of the mass itself its temperature would be lowered and a slightly greater amount of crystals formed. The net result would be, however, a marked change in the composition of the inclusions, a moderate decrease in the actual amount of solid material with corresponding increase in the amount of liquid. The liquid, too, becomes more albitic, that is, is pushed onward upon its normal crystallization course.

If, instead of inclusions of Ab_1An_1, more sodic inclusions were added, say Ab_2An_1, there would be a somewhat greater increase in the amount of liquid and a markedly greater enrichment of the liquid in more albitic plagioclase. Inclusions as rich in albite as $Ab_{10}An_1$ might be completely melted by the liquid before becoming

a part of the general liquid, their melting being accomplished by precipitation of more basic plagioclase.

Summing up the result of adding to a liquid various members of a solid solution series with which it is saturated we find that if the added inclusion is nearer the high temperature end of the series than the crystals with which the liquid is saturated the reaction is such as to decrease the amount of liquid and is exothermic. If the inclusion is nearer the low-temperature end of the series than the crystals with which the liquid is saturated, the reaction is such as to increase slightly the amount of liquid and is endothermic. The liquid, too, is enriched in this case in the constituents of the low-temperature end of the crystallization series. Even inclusions consisting of the precise crystals with which the liquid is in equilibrium must react with the liquid as the temperature falls.

Whatever the composition of the inclusions, then, the liquid may show very marked effects upon them even though it is saturated, and consequently such effects would not constitute evidence of superheat. A little consideration will show, too, that these reactions have no significant effect upon the course of the liquid. Regarding the progress of the liquid as resulting from fractional crystallization, the liquid will in all cases run along the boundary curve (*ED*) as the temperature falls. The point it will eventually reach on this curve will depend upon the perfection of fractionation which in turn depends upon the rate of cooling. Inclusions of the more calcic kind tend to limit the career of the liquid by using it up, but at the same time furnish heat that tends to slow up the rate of cooling. Inclusions of the more sodic kind tend to push the liquid onward upon its course of crystallization, but hasten the cooling. The original unaffected liquid has all the differentiation potentialities that the liquid has after entering into the reactions mentioned.

REACTION SERIES

In the discussion relative to liquids of the diopside:anorthite: albite system nothing has been said regarding the effect of adding solid diopside to liquids saturated with diopside for the reason that there is no effect. The solid diopside simply remains as such on account of its being a pure compound of definite composition. But

rock-forming minerals are seldom so simple. Quartz is the only important example of a rock mineral of definite composition, practically all others being of a variable nature, that is, solid solutions. The rock-forming pyroxenes do not fall behind in this respect and the addition of pyroxene to a natural magma saturated with pyroxene would in general be attended by reaction phenomena similar to those we have described for the plagioclases. The precise nature of the reactions in the case of the pyroxenes cannot be stated except for the clino-enstatite-diopside solid solution series.[1]

In another paper the writer has discussed solid solution series and offered reasons for calling them *continuous reaction series*. The importance of the reaction relation between liquid and crystals was there discussed in its bearing on crystallization. Here we have seen its importance in connection with the behavior of inclusions.

As was pointed out in the paper referred to, there is another type of reaction relation between liquid and crystals that is exhibited in the *reaction pair* and the *discontinuous reaction series*.[2]

The existence of such series is again of great significance in connection with the behavior of inclusions. An important reaction pair are the olivine, forsterite, and the pyroxene, clino-enstatite. Their relation is exhibited in its simplest form in the binary system, forsterite-silica, of which the equilibrium diagram is shown in Figure 7. The effect of adding crystals of the first member of a reaction pair to a liquid saturated with the second member is well illustrated by this system. A liquid of composition (*M*) is saturated with clino-enstatite but lies on the unsaturated side of the metastable prolongation of the forsterite liquidus. It is therefore unsaturated with forsterite and we may imagine that around each added forsterite crystal a small quantity of liquid of composition (*N*) may form. This condition is, however, metastable and from this liquid clino-enstatite would immediately be precipitated with formation of the liquid (*M*). Through constant repetition of this formation from forsterite of an infinitesimal quantity of the metastable liquid, with immediate precipitation of clino-enstatite, the forsterite is

[1] N. L. Bowen, *Amer. Jour. Sci.*, Vol. XXXVIII (1914), pp. 228–37.

[2] "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

converted into clino-enstatite. Effectively, then, the liquid (*M*) is supersaturated with forsterite. It cannot dissolve forsterite but can only convert it into clino-enstatite, the phase with which it is saturated. This principle is capable of general application and we may state that a liquid saturated with any member of a discontinuous reaction series is *effectively* supersaturated with all higher members of the series; it cannot dissolve them but can only convert them into the phase with which it is saturated.

In connection with the specific case we have discussed, it should be noted that the amount of clino-enstatite formed is not simply the

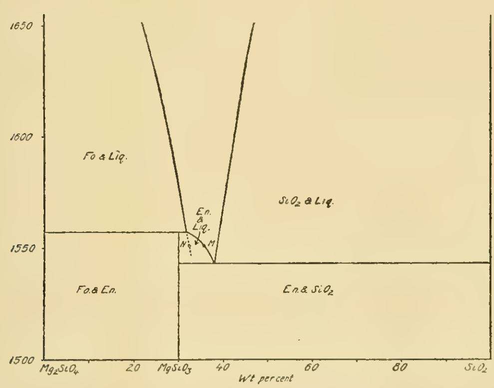


FIG. 7.—Lower temperature portion of the equilibrium diagram, forsterite-silica

chemical equivalent of the forsterite changed. The chemical equivalent would be somewhat less than one and one-half times the forsterite, whereas the amount of clino-enstatite formed is much greater, being in fact about five times the amount of forsterite. In other words, the action is not simply an addition of silica to the forsterite, with consequent impoverishment of the liquid in silica, for the liquid cannot have silica subtracted from it without passing under the clino-enstatite saturation curve, that is, without precipitating clino-enstatite. In order to convert the forsterite inclusions into clinoenstatite, the liquid must precipitate a large amount of clino-enstatite from its own substance, and the action uses up a large amount of the liquid. The liquid left has, however, in this binary case, the same composition as the initial liquid, if the temperature is kept

constant. The liquid is not at all desilicated, even though it has caused the conversion of the inclusions into a more siliceous phase. By precipitation of the phase with which it is saturated, it has adjusted its composition in such a way as to remain on the same saturation curve. This again is a principle that can be applied in general to the reaction between a liquid and inclusions belonging at an earlier stage of the reaction series than the phase with which the liquid is saturated.

Further considerations relative to this reaction pair will be developed in connection with their behavior in the more complex liquids containing anorthite as worked out by Andersen[1] and shown in Figure 8. From this figure we may very readily predict what would happen to "inclusions" of the various solid phases immersed in liquid. Let us take first a liquid just saturated with forsterite (say M at 1450°). Ordinarily crystals of forsterite would separate first; they would then react with liquid to form pyroxene; pyroxene would continue to separate for a time and would then be joined by silica; finally, at the ternary eutectic 1222°, anorthite would join these, and the product would consist of pyroxene, silica, and anorthite. If to the original liquid some "foreign inclusions" of forsterite were added the liquid would, on cooling, attempt to make the forsterite over into pyroxene, but now there would not be enough liquid to accomplish this entirely, and it would be used up at 1260° while there was still some forsterite left; so that the solidified mass would now consist of pyroxene, forsterite, and anorthite. Thus we see that even though it is precisely the substance with which the liquid is in equilibrium, the addition of forsterite has a considerable effect upon the crystalline product formed. The exact effect is a tendency to limit the scope of the products to the early members of the crystallization sequence. In this case, silica, a later member of the sequence, does not appear. It is plain, too, that the effect does not depend on the particular properties of this reaction pair and that we may conclude that it would be true of any discontinuous reaction series. We have already seen that the same effect is found in the continuous reaction series (solid solution series). We may

[1] The system anorthite-forsterite-silica, *Amer. Jour. Sci.*, Vol. XXXIX (1915), p. 440.

state it as a general law therefore that a saturated liquid in any system dominated by reaction series will not remain indifferent to inclusions even of the exact composition with which it is in equilibrium, and that the effect of the addition of such inclusions is a tendency to limit the scope of the crystalline products to adjacent members of the reaction series involved.

Let us now examine what happens when inclusions of an early member of a discontinuous reaction series (or reaction pair) are added

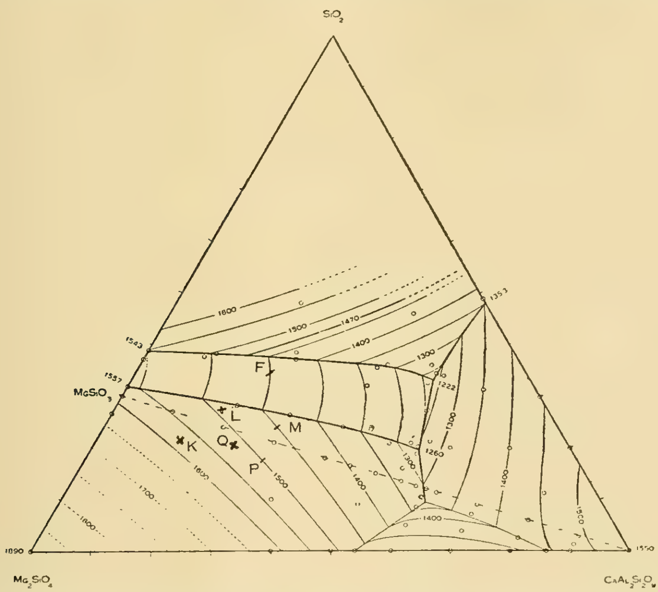


FIG. 8.—Equilibrium diagram of the system anorthite-forsterite-silica. (After Andersen.)

to a liquid saturated with a later member. The liquid *F* is just saturated with clino-enstatite at 1450°. If it is cooled, clinoenstatite will separate first, it will later be joined by silica and then by anorthite, when the whole mass will solidify at 1222°. But if inclusions of forsterite are added to this liquid it will instantly start to react with these inclusions and make them into the mineral with which it is saturated, viz., clino-enstatite. If there is perfect opportunity for reaction we may readily predict what the end result will be for varying amounts of added inclusions.

Suppose first that the amount of inclusions was such as to give a total composition represented by the point K. The liquid would then be completely used up by the reaction while some inclusions yet remained, so that the finally solidified mass would consist of forsterite, clino-enstatite, and anorthite. If, on the other hand, the amount of inclusions was such as to give a total composition represented by the point L, all the inclusions would be changed to clino-enstatite while some liquid yet remained, and this liquid would then pass onward to the deposition of silica and anorthite in the ordinary way. Thus the addition of inclusions of this kind, if in sufficient quantity, restricts the career of the liquid and confines the crystalline products to adjacent members of the reaction series.

It is perhaps not necessary to add that if the liquid did not react with the inclusions no effect on the course of the liquid would ensue.

Just as was the case in the binary system, the liquid is not desilicated by this addition of silica to the forsterite inclusion, but by precipitating an appropriate amount of the phase with which it is saturated (clino-enstatite), it maintains its position on the same (clino-enstatite) saturation surface.

Nothing has been said of the heat effect of this reaction and it has been tacitly assumed that the temperature remains constant. The reaction is, in fact, exothermic, as can be readily shown by applying the same reasoning as was applied to the similar case in a continuous reaction series. If no heat were abstracted from the system it would heat itself up and equilibrium would be established at a slightly higher temperature with a somewhat more magnesian liquid than the initial liquid. But the formation of this somewhat more magnesian liquid is not properly to be taken as an indication that the net result of the process is a direct solution of some of the inclusions. A direct solution of inclusions would mean a decrease in total solids and an increase in liquid, whereas the reaction referred to results in a diminution in the amount of liquid and a corresponding increase in the amount of solids even when this heating effect takes place. If heat is being taken from the system this process would act as a deterrent upon the rate of cooling.

All of these effects we have found to be true of analogous inclusions in the case of the continuous reaction series.

There is yet to be examined the example in which a late member of a discontinuous reaction series is added to a liquid saturated with an early member. To the liquid *P* at 1500°, where it is just saturated with forsterite, inclusions of clino-enstatite are added in an amount sufficient to give a total composition *Q* (about 20 per cent). If the temperature were kept constant equilibrium would be established when the mass consisted of 4 per cent forsterite and 96 per cent liquid, that is, the inclusions have been changed into the phase with which the liquid is saturated and there has been an increase in the amount of liquid. In order to effect this change heat would have to be added to the system. If the system is self-contained, that is, if the only heat available is the heat of the system itself, a cooling would result and this would necessitate the crystallization of a further amount of forsterite until the necessary heat was supplied by this crystallization and the cooling of the mass. The net result would depend entirely on the relative heats of solution of forsterite and clino-enstatite in the liquid. These are probably of the same order of magnitude, so that equilibrium would be established at about 1475° when the mass consisted of 10 per cent forsterite and 90 per cent liquid approximately. The net result, then, has been the conversion of the inclusions added (clino-enstatite) into the phase with which the liquid is saturated (forsterite), an enrichment of the liquid in the material added, with, at the same time, a pushing onward of the liquid along its usual course of crystallization. Or it could be stated that the inclusions pass into solution by precipitating their heat equivalent of the phase with which the liquid is saturated.[1] This, then, is the result of adding inclusions which belong to a discontinuous reaction series and are later in that series than the phase with which the liquid is saturated. It is sensibly the same result as that obtained in the corresponding case in the continuous reaction series.

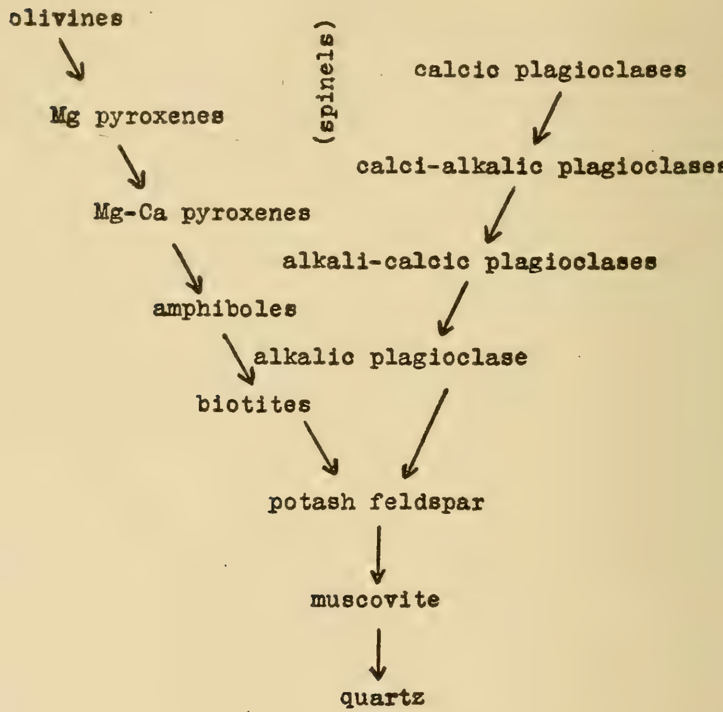
EFFECTS OF MAGMA UPON INCLUSIONS OF IGNEOUS ORIGIN

In the paper in which the conception of the reaction series was developed it was shown that these series are very prominent in rocks. An attempt was made there to arrange the minerals of rocks as

[1] This is only approximately true, for equilibrium is always established at a somewhat lower temperature and the cooling of the mass supplies a little of the heat.

reaction series and it was found that there are, toward the basic end of rock series, two fairly distinct reaction series that finally merge into one in the more acid rocks. This was expressed diagrammatically as follows.

TABLE II



On the basis of the principles that we have found to govern the behavior of inclusions belonging to reaction series we may deduce with considerable confidence the effects of liquid upon inclusions in this more complex series.

It may be stated immediately that any magma will tend to make inclusions over into the phase or phases with which it is saturated, in so far as the composition of the inclusions will permit. It may be stated also that any magma saturated with a certain member of a reaction series is effectively supersaturated with all higher members of that reaction series. It cannot, in any sense, dissolve inclusions

of such higher members but can only react with them to convert them into that member of the reaction series with which it is saturated, often by passing through other members of the series as intermediate steps. The material used to effect these changes cannot be regarded as simply subtracted from the liquid for the liquid is not free to become impoverished in any random substance. In general impoverishment in any substance will cause the liquid to pass within a region of saturation and induce the precipitation of some of the phases with which the liquid is saturated.

Let us take, for example, a magma saturated with biotite, say, a granitic magma. This magma is effectively supersaturated with olivine, pyroxene and amphibole and cannot dissolve them in spite of the marked contrast of composition, which is often supposed to be an aid to the solution of inclusions. But the magma can and will react with these minerals and convert them into biotite, usually by steps. The subtraction of material necessary to produce biotite will cause the precipitation of the minerals with which the magma is saturated until either the liquid or the inclusions are used up or the reaction is brought to an end on account of mechanical obstruction.

Similarly, granitic magma saturated with an acidic plagioclase cannot dissolve basic plagioclase but can only react with it and convert it into more acid plagioclase.

These remarks are tantamount to the statement that saturated granitic magma cannot dissolve inclusions of more basic rocks. The magma will, however, react with the inclusions and effect changes in them which give them a mineral constitution similar to that of the granite. These changes will often be accompanied by disintegration of the inclusions and the strewing about of the products which may be indistinguishable from the ordinary constituents of the granite. The inclusions may thus become completely incorporated though not in any sense dissolved. It is this action of magmas upon inclusions that makes particularly difficult the problem of distinguishing xenolith from autolith, i.e., accidental inclusion from cognate inclusion.

Whatever origin one may assign to a granitic magma—let it be formed by differentiation of more basic magma, by differentiation of syntectic magma or by palingenesis of sediments—there seems no

escape from the conclusion that it will normally be saturated. The normal effect of granite upon more basic inclusions should therefore be such as has been outlined above. Thus we find that Fenner, in describing the action of granitic magma on basic bands in an injection gneiss, says, "In other places the dark minerals appear to have been taken up or digested by the magma and to have crystallized out again in large blades. Even in the latter case it is not always certain that perfect solution has been effected at any one time. The process may have been rather in the nature of a chemical reaction with the original minerals or the solution and redeposition of a portion of the material at a time,[1] leaving the general relations undisturbed. This possibility is suggested by the fact that frequently even the coarser micaceous blades or aggregates of dark minerals show evidence of parallelism and this would be difficult to account for under the supposition that solution was so perfect that the original structure was completely wiped out."[2] Here, apparently, we have a good example of the transformation, by reaction rather than solution, of the dark bands into mica-rich material, mica being the dark mineral with which the magma is saturated. The change of serpentine into biotite as observed by Gordon at the borders of granitic pegmatites is precisely the action to be expected.[3]

V. M. Goldschmidt describes the strewing about of the minerals of a basic hornfels in magmas of the Christiania region. He says, "This strewing about hardly has its origin in a solution of the minerals and their later separation. Had solution occurred the grains would not have retained their original forms and they would have differed in composition from the minerals of the hornfels." Near the border of an apophysis of the nordmarkite, grains of diopside from the hornfels are surrounded by a rim of aegirite. In the center of the apophysis the aegirite has no core of diopside.[4]

[1] Note discussion on p. 532.

[2] C. N. Fenner, "The Mode of Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, Vol. XXII (1914), pp. 602–3.

[3] "Desilicated Granite Pegmatites," *Proc. Acad. Nat. Sci. Phila.*, Part I (1921), p. 169.

[4] V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristianiagebiet," *Vid. Selsk. Skr. I. Mat. Naturv. Klasse* (1911), No. 1, pp. 107–8.

In the foregoing discussion granitic magma has been taken merely as an example to which the principles developed may be applied. As a further example it may be pointed out that saturated dioritic magma cannot dissolve inclusions of gabbro, peridotite or pyroxenite but, given the opportunity, it will react with those inclusions and convert them into the hornblende and the plagioclase with which it is saturated, at the same time precipitating a further amount of this hornblende and plagioclase from its own substance.

These are but examples of the application of the principle that a saturated magma cannot dissolve inclusions of material farther back in the reaction series (in general more basic) than the crystals with which it is saturated. At the same time the magma can attack these inclusions, reacting with them in such a manner as to convert them into the crystals with which it is saturated.

The dioritic magma we have considered will not remain indifferent to inclusions even of the exact composition of the crystals with which it is in equilibrium, for as the temperature falls it will modify the composition of these inclusions just as it modifies the composition of its own crystals. Indeed this case may be regarded as a special case of that just discussed, for, as the temperature falls, the composition of the liquid changes, and the inclusions then pass into the class of those considered above.

We now come to the case of inclusions of material later in the reaction series than the crystals with which the liquid is saturated. It should be noted that this includes masses of rock of the same composition as the liquid itself, for example its own chilled border phase.

Saturated basaltic magma can react with inclusions of igneous rocks later in the reaction series (in general more acid) in such a way that the inclusions become part of the liquid, crystals of the phases with which the basalt is saturated being precipitated at the same time. If these crystals are removed by gravity or otherwise the action on the inclusions may continue, the liquid changing in composition toward the composition of the inclusions and precipitating later and later members of the reaction series until finally it is saturated with precisely the crystalline phases contained in the inclusions. If granitic inclusions, say, were available at the upper contact of a mass of basaltic magma, they would be attacked by the

magma in the manner noted and, in a lower layer, accumulation of the precipitated products of the reaction would take place. These would be the early crystals formed in basaltic magma. The upper liquid is thus gradually changed in composition and the crystals precipitated from it are successively later and later members of the reaction series. Attack upon the inclusions continues until finally the upper liquid becomes granitic. All of this depends on a rate of cooling slow enough for free crystal settling to occur. But if the cooling is sufficiently slow for crystal settling all of these results could accrue from the simple differentiation of the basaltic magma. Indeed the principles developed show that the inclusions can become part of the liquid only when they have a composition toward which the composition of the liquid can vary by spontaneous differentiation.

Nevertheless it is apparent that the amount of granitic differentiate might be greatly augmented by this action. It may safely be assumed therefore that in many individual cases considerable quantitative importance in the production of a granitic differentiate of basic magma is to be assigned to the action noted. It is a sort of solution of granitic inclusions though not a simple, direct solution and is in no sense essential to the production of a granitic differentiate.

Daly is of the opinion that many granites are secondary, that is, are formed by solution of granite in basaltic magma and subsequent differentiation.[1] It is seen from the above that theoretical considerations support belief in a process which, in its results at least, is practically that advocated by Daly. The process itself he considers to be rather a simple solution of granite in superheated basaltic magma. We have seen that no superheat is necessary to produce solution by a sort of reactive process. Moreover, we have seen that the incorporated granitic material is to be regarded rather as a contribution to the normal granitic differentiate. There appears, however, to be no reason to doubt that, at times, this contribution might equal or possibly even exceed in amount the granitic differentiate capable of formation from the uncontaminated magma.

[1] Indeed, Daly derives in this manner all granites except a supposed original granitic shell of the earth (*Igneous Rocks and Their Origin*, p. 323).

The limiting factors are principally mechanical rather than thermal or chemical and are very difficult to evaluate. It should be noted, in particular, that the combination which is most favorable for significant effects in the way of reactive solution, viz., decidedly acid inclusions and decidedly basic magma, is unfavorable in another respect. The inclusions will be lighter than the magma and will not tend to sink in it, whereas it is the sinking of inclusions through the magma which favors particularly notable reaction effects since it continually brings new magma into contact with the inclusions.

As an example of the effect of basic magma on more acid igneous inclusions basaltic magma and granitic inclusions have been taken. Between such extremes the more marked effects should be obtained, but it cannot be doubled that any basic magma can dissolve, by the same reactive process, inclusions of a rock later in the reaction (crystallization) series. Direct melting of granitic inclusions to masses of liquid by basaltic magma is not ordinarily to be expected because the solid granite does not retain the volatile components that aid in lowering the melting temperature of granitic magma below that of basaltic magma. This lack is no bar to the reactive solution process described, though it may limit it somewhat.

EFFECTS OF MAGMA ON INCLUSIONS OF SEDIMENTARY ORIGIN

The general problem of the effects of magma upon inclusions of sedimentary origin is much more difficult than the similar problem in connection with igneous inclusions. Sedimentary rocks have their compositions determined by processes wholly independent of igneous action and do not correspond in composition with the products precipitated from magmas at any stage of their career, that is, cannot be placed definitely in the reaction series. However, certain minerals that can be formed in magmas do occur in the sedimentary rocks and often the composition of a sediment is such that by mere heating it can be transformed into an aggregate made up exclusively or almost exclusively of igneous rock minerals. Again sediments exhibit extremes of composition, being very rich in calcium carbonate, aluminum silicate or silica itself, and these present a special problem. Yet it is perhaps not generally realized how

much even of these extreme sediments might be incorporated in an igneous rock without changing its mineralogy. The fact is an obvious deduction from the equilibrium diagram of any investigated three component system and it is equally true of a more complex system. Figure 9 shows the solid phases formed immediately upon complete consolidation of any mixture of CaO, Al_2O_3 and SiO_2. A mixture of composition (*A*) consists, upon complete consolidation, of anorthite, wollastonite, and gehlenite, one third of each. One may

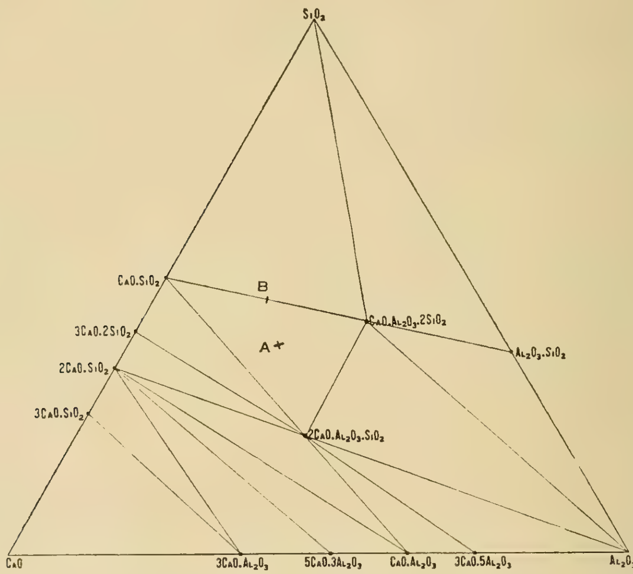


FIG. 9.—Diagram of the system CaO-Al_2O_3-SiO_2 showing phases formed upon complete consolidation. (After Rankin and Wright.)

add to this mixture any amount of CaO up to about 15 per cent of itself, without changing the mineral composition of the consolidated product. Similar amounts of either Al_2O_3 or SiO_2 might be added, the only change in all cases being in the relative amounts of the minerals, not in the kind of minerals. A certain amount of change in the order of separation of the minerals would be effected but the temperature of final consolidation, the composition of the final liquid and the possible differentiates that might be formed by fractional crystallization would in all cases remain as before. Only

when amounts are added in excess of those mentioned will a new crystalline phase appear and new fractionation possibilities enter.

There are, however, certain mixtures in the system that will immediately present a new phase upon addition of the slightest amount of CaO, Al_2O_3, or SiO_2. Such is the mixture (*B*) which consists on consolidation of anorthite and wollastonite, one half of each. The addition of either CaO or Al_2O_3 will bring in the new phase, gehlenite, and of SiO_2 the new phase, tridymite, and each will change the course of crystallization. This is because the composition chosen is a limiting case in the ternary system and is in reality of only two components; and the addition of, say, lime carries it out of the two component system. It will be noted that the mixture considered contains the three oxides, though of only two components, and on consolidation only two solid phases are formed. It might seem on first thought that this corresponds with the case of the natural magmas, for these usually form solid phases fewer in number than the oxides present. However, there is another factor, namely, solid solution, that may give rise to this peculiarity and we shall find that it is to solid solution that the limited number of phases formed from magmas is usually to be referred.

Let us now examine a ternary system of oxides that has been completely investigated and in which the factor of solid solution enters. Such is the system CaO:MgO:SiO_2 studied by Ferguson and Merwin.[1] A liquid of composition *A*, Figure 10, forms on complete consolidation just two solid phases, the olivine, forsterite, and clinopyroxene of composition between diopside and $MgSiO_3$. To this liquid any amount of calcite up to 12 per cent of its weight could be added without changing the mineralogy of the consolidated product. This would still consist of olivine and clinopyroxene but the pyroxene would be richer in CaO, that is, closer to diopside. Only an amount of calcite in excess of 12 per cent would bring in another phase, akermanite, together with the diopside and olivine. It is easy to see from an inspection of the figure that addition of dolomite would likewise have no effect on the kind of phases crystallizing unless more than about 16 per cent were added.

[1] *Amer. Jour. Sci.*, Vol. XLVIII (1919), p. 109.

When we have spoken of adding calcite and dolomite to the mixtures mentioned we have imagined that the lime and magnesia have been taken into solution as they might be in a laboratory furnace where the furnace supplied the requisite quantity of heat. This quantity would be very large, for the conversion of carbonate into silicate is an endothermic reaction and its conversion into silicate in solution is undoubtedly still more strongly endothermic. Now if the liquid were originally a saturated liquid and calcite or

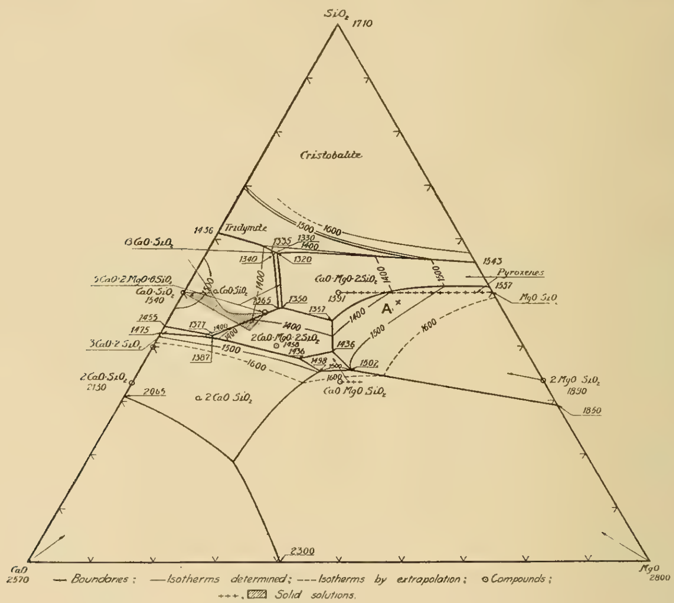


FIG. 10.—Equilibrium diagram of the system CaO-MgO-SiO_2. (After Ferguson and Merwin.)

dolomite were added without any provision for additional heat other than that already contained in the liquid, the lime and magnesia would not be simply dissolved. Instead, precipitation of olivine (forsterite) would occur, no matter whether calcite or dolomite was added, and as the forsterite separated the liquid would attack the calcite, converting it into lime silicates. Since this is an endothermic reaction the heat for it can be supplied only by crystallization of something from the liquid which will be, of course, the phase with which it is saturated, viz., forsterite. There is another

reason why forsterite is precipitated for the formation of lime silicates requires some silica but the liquid cannot be desilicated since it lies on the forsterite saturation surface. Therefore the liquid changes its composition by moving on the forsterite surface toward lower temperature. It does not move directly away from forsterite, however, but curves somewhat in the direction of the composition of the inclusions. If the reaction with the inclusions is strongly endothermic, as it is in this case, the liquid would move down to the forsterite-pyroxene boundary curve where separation of pyroxene would occur and the liquid would be entirely used up without ever getting over to such compositions that akermanite would separate from it. However, some part of the inclusions might have been converted to akermanite. Thus, however large a supply of inclusions were available, even in excess of the 12 per cent mentioned above, the liquid might never get over to such compositions that any new phase is precipitated from it, but would precipitate only forsterite and pyroxene as in normal crystallization, with, however, a certain increase in the lime content of the pyroxene.

These considerations lead us to the conclusion that the liquid we have chosen, even if it has a moderate amount of superheat and therefore is capable of directly dissolving a little lime and magnesia from calcite or dolomite, does not suffer a change in the kind of solid phases capable of forming from it. There results only a modification of the composition of the phase of variable composition (pyroxene). And, as a consequence of the heat effect of the solution of inclusions, saturation shortly ensues and thereafter further action upon the inclusions is accomplished only with concomitant precipitation of the phase or phases with which the liquid is saturated, whereby the liquid is constrained to follow a general course not significantly different from the one it would follow were no inclusions present.

The results obtained in the foregoing enable us to draw certain conclusions as to the effects of natural magmas upon inclusions of various sedimentary rocks. One point that does not seem to be realized is that when a sedimentary inclusion becomes immersed in a magma nothing is added that the magma does not already contain. Both belong to the same polycomponent system embracing all the

rock-forming oxides. Obviously the effects of all possible sediments cannot be examined, but our purpose will be served if we take the most extreme departure from igneous composition. As representative of this condition, for quartzite we may imagine the addition of pure quartz; for limestone, of pure calcium carbonate; and for shale, of pure kaolin. Any actual sediment would usually contain all of these, together with other constituents that lessen its departure from igneous composition.

Let us take a magma of basaltic composition which, on crystallization with comparatively rapid cooling, would form mainly plagioclase, and clinopyroxene, with some olivine, a little ore mineral and possibly some orthopyroxene. All of these are minerals of variable composition; some of them, in particular the pyroxene, vary with respect to several components and to this is to be attributed the fact that the number of solid phases formed is less than the number of oxides present. This fact permits particularly wide adjustments in the composition of the solid phases without the appearance of new ones. Such basaltic magma, with a little superheat, could directly dissolve a moderate amount of sediments, yet even if these were of extreme composition the magma would crystallize with the production of the same solid phases as those mentioned above if crystallized under the same conditions.

Normally only saturated magma would be available and the superheated magma mentioned above would rapidly become saturated as a result of solution of inclusions. For the case of such saturated magma it may be stated as a first principle that the sediment would, in so far as its composition permitted, tend to be converted into the phases with which the magma is saturated. And the material necessary for such changes in the sediment would not be merely subtracted from the liquid but adjustments of the composition of the liquid would occur through separation of further amounts of the phases with which the liquid is saturated.

The precise changes in the composition of the solid phases formed cannot be represented graphically on account of the number of components involved, but equations can be written that afford a generalized conception of the possible adjustments for the addition of calcite, silica, and kaolin respectively.

The phases capable of formation from the original unchanged magma are:

Phase	Mineral molecules represented
Olivine	$Mg_2SiO_4+Fe_2SiO_4$
Magnetite	$FeO.Fe_2O_3$
Plagioclase	$CaAl_2Si_2O_8$+etc.
Pyroxene	$CaMgSi_2O_6+MgSiO_3+Al_2O_3{}^*+CaFeSi_2O_6+FeSiO_3+Fe_2O_3{}^*$

* Often written as existing in the Tschermak molecule, for which there is no good reason. See Washington and Merwin, *Amer. Jour. Sci.*, Vol. III (1922), p. 121.

Upon addition of CaO the following principal adjustments in the proportions of these mineral molecules may occur without the appearance of new phases:

$$CaO+2FeSiO_3+Fe_2O_3=CaFeSi_2O_6+FeO.Fe_2O_3;$$
$$CaO+3MgSiO_3=CaMgSi_2O_6+Mg_2SiO_4;$$
$$CaO+Al_2O_3+4MgSiO_3=CaAl_2Si_2O_8+2Mg_2SiO_4.$$

Upon addition of SiO_2:

$$SiO_2+Mg_2SiO_4=2MgSiO_3;$$
$$SiO_2+Al_2O_3+CaMgSi_2O_6=CaAl_2Si_2O_8+MgSiO_3.$$

Upon addition of kaolin, which we may regard as $Al_2SiO_5+SiO_2$, with SiO_2 having the same effect as above:

$$Al_2SiO_5+CaMgSi_2O_6=CaAl_2Si_2O_8+MgSiO_3.$$

The results may be put in words by stating that addition of lime tends to increase the amount of magnetite and olivine, to make the pyroxene more nearly a pure diopside-hedenbergite and to increase the anorthite content of the plagioclase. The addition of silica tends to decrease the amount of olivine and to increase the magnesian content of the pyroxene and the anorthite content of the plagioclase. The addition of kaolin tends to increase the amount of magnesia in the pyroxene and of the anorthite in the plagioclase.

In the case of superheated magma the added material might be directly dissolved and upon solidification the adjustments noted would appear in the crystalline phases. In the case of saturated magma the phases noted would be developed by reaction with the added material and at the same time a further amount of them would be precipitated from the liquid. In neither case would the course of crystallization be fundamentally changed since crystalliza-

tion produces only the same solid phases slightly modified in composition. If consolidation took place under conditions permitting fractionation by settling of crystals no fundamentally new differentiation potentialities would be introduced by the solution or reaction with foreign material that has been discussed. The magma thus modified could give a diorite-granodiorite-granite sequence, say, only if the original magma could also have done so under the same conditions. It is a question whether, in the case of unsaturated magma, it can be safely assumed that the degree of superheat may be such that an amount of material can be dissolved in excess of that which can be taken care of by the adjustments in composition of existent phases. If this is possible new phases will appear and the course of crystallization and differentiation might be fundamentally modified. In the case of added CaO, for example, the new phase melilite might appear and the differentiates formed might be fundamentally different; might be, say, certain alkaline types as Daly has postulated.

EFFECTS OF BASALTIC MAGMA ON ALUMINOUS SEDIMENTS

With this possible exception in the event of excessive superheat, the statement should hold that reaction with foreign material can produce no new differentiation potentialities in the magma. Yet it is certain that some lines of differentiation may be emphasized by such agency, that is, that certain types of differentiate should be quantitatively of greater importance. This we have found to be true of reaction of magma with previously solidified igneous material. Thus when basaltic magma reacts with granitic material the tendency is to increase the amount of granitic differentiate capable of forming from the basalt. The effect of reaction with aluminous sediments is of sufficient importance to justify further discussion at this point. The result has been shown to be the emphasizing of more magnesian pyroxene and of anorthite. Now under certain conditions, not well understood, magnesian pryoxene separates from magmas as a distinct phase, an orthopyroxene, and the addition of aluminous sediments should emphasize this tendency. The formation of norite and of pyroxenites characterized by orthopyroxene as differentiates from basaltic magma, may therefore be facilitated by

reaction of such magma with aluminous sediments. A suggestion along similar lines has already been made by Evans.[1]

An example of the reaction of basic magma with aluminous sediments, in which the relations discussed seem particularly clear, is afforded by the so-called Cortlandt series.[2] The early work of Williams and the later work of Rogers on this series treats in some detail the features bearing upon the question here at issue.[3] The Cortlandt series is intrusive into the Manhattan schist (locally into

TABLE III

	I	II
SiO_2	57.94	40.16
Al_2O_3	21.70	29.50
Fe_2O_3	1.57	19.66
FeO	5.90	5.80
MgO	2.49	trace
CaO	.58	.85
Na_2O	1.74	1.46
K_2O	4.68	1.36
H_2O+	2.17	....
H_2O-	.29	....
TiO_2	1.01	....
MnO	.19	....
S	....	.82
	100.26	99.61

I. Manhattan schist. Composite analysis of five specimens beyond border of the Cortlandt series. Analyst, G. S. Rogers.

II. Manhattan schist on contact of Cortlandt series. Analyst, F. L. Nason in G. H. Williams, *Amer. Jour. Sci.* (3), Vol. XXXVI (1888), p. 259.

other formations also) and the interaction between schist and magma is in places rather well displayed. The Manhattan schist is a metamorphosed sedimentary rock of the nature of a shale. Its composition, as given by a composite analysis of five specimens, is shown in Table III under I. No doubt it varies considerably from this average and is sometimes more aluminous, but it is always far from the composition of kaolin, which composition we have used

[1] J. W. Evans in discussion of paper by C. E. Tilley, *Quar. Jour. Geol. Soc.*, Vol. LXXVII, p. 133.

[2] G. H. Williams, *Amer. Jour. Sci.* (3), Vol. XXXI (1886), p. 26; (3), Vol. XXXIII (1887), pp. 135, 191; (3), Vol. XXXV (1888), p. 438; (3), Vol. XXXV (1888), p. 254.

[3] G. S. Rogers, *Ann. N.Y. Acad. Sci.*, Vol. XXI (1911), pp. 11–86.

in discussing the effects of basic magma on aluminous sediments. This affords an opportunity of discussing the behavior of an actual example of aluminous sediment. The ordinary Manhattan schist is made up principally of the minerals quartz, biotite, muscovite, orthoclase and plagioclase. These are all minerals of ordinary igneous rocks, particularly of more "acid" types, and correspond to a rather low temperature equilibrium. A glance at the analysis shows, however, that the composition is far from that of an ordinary igneous rock, which means that the minerals are of somewhat different composition and are present in different proportions. Now we have found in our discussion of the reaction of any saturated magma upon igneous inclusions that if the inclusions belong to a later stage in the reaction series they may become a part of the liquid by causing the precipitation of the phases with which the liquid is saturated. Average Manhattan schist, since it consists of the minerals of an acidic igneous rock, may be regarded as consisting in part of material belonging to a later stage in the reaction series than basaltic magma, but since it does not correspond exactly with any such igneous mass it must be regarded as having a certain amount of surplus material in addition. If we imagine saturated basaltic magma reacting with inclusions or wall rock of schist we may expect the action to be selective. Such substances as may become a part of the liquid would be removed from inclusions or wall rock with corresponding enrichment in what has been called surplus material. The substances removed would be principally silica, alumina, alkalis and to a minor extent other oxides, all in the proportions in which they enter into some "acid" igneous rock. Our knowledge of the exact proportions may be thus indefinite and yet sufficient for a general solution of the problem. Comparison of the analysis of the Manhattan schist with those of acid igneous rocks gives us a good conception of what the surplus material will be. It will plainly be rich in alumina and iron. A certain stage of the reaction between magma and inclusions or wall rock should exhibit a mass rich in these oxides. This stage is abundantly represented in both wall rock and inclusions by richness in sillimanite, staurolite and other aluminous and ferrous minerals. Chemically it is shown by analysis II in Table III which represents wall rock at the margin of the intrusive.

The so-called surplus material does not remain indefinitely as such, but by the time we have obtained inclusions very rich in sillimanite a turning point in the process is reached. Hitherto certain constituents of the schist have become a part of the liquid in virtue of the precipitation of various phases with which the liquid (magma) was saturated. Now reactions between magma and inclusions become of such a nature that the precipitation of phases with which the magma is saturated is the sole process, these phases being appropriately modified by the inclusions. There is now no addition to the liquid. The exact modification of the phases that is produced by sillimanite has already been discussed and equations representing the changes have been written. The net result is an increase in the amount of anorthite and magnesian pyroxene at the expense of lime-bearing pyroxene, and this tends to promote the separation of magnesian pyroxene as a distinct phase, orthopyroxene. Thus the tendency of the magma to give a noritic differentiate is increased, as well as the likelihood of formation of a pyroxenite containing orthopyroxene. These expectations are well matched by the Cortlandt series.

Apart from possible later differentiation this production of norite and related types is the end result of the action of basic (basaltic) magma on sillimanite-rich inclusions. We may with profit examine the details of the action, that is, the processes going on within and immediately around the sillimanite-rich inclusions immersed in a magma rich in plagioclase and pyroxene. This examination serves to throw some light on the detailed mineralogy of the inclusions, and in particular on the separation of free alumina, as corundum.

If a mass of sillimanite were added to some anorthite just above its melting point, it can be readily seen from examination of Figure 11 that some of the sillimanite would be converted into corundum. This is because the line joining sillimanite and anorthite passes through the corundum field. We may imagine, for example, that the bulk composition of a layer immediately surrounding the sillimanite is 50 per cent sillimanite and 50 per cent anorthite. The mixture represented by this layer, at 1550°, would consist of sillimanite, corundum, and liquid. If the original anorthite liquid had an

excess of silica amounting to about 10 per cent, no corundum would be formed from sillimanite, because the join of sillimanite with such a composition misses the corundum field. Plainly the freeing of corundum from sillimanite depends in these liquids on the liquid being "basic," that is, having not more than a moderate excess of silica over the feldspar composition. Free silica associated with

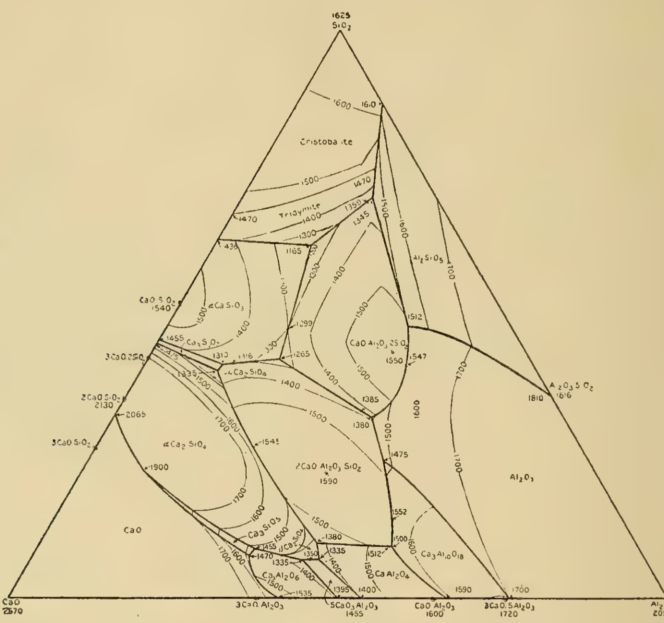


FIG. 11.—Equilibrium diagram of the system CaO-Al_2O_3-SiO_2. (After Rankin and Wright.)

the sillimanite does not have a comparable effect in restricting the formation of corundum; indeed, the silica would require to be nearly equal in amount to the sillimanite in order to neutralize the tendency to form corundum.

The system $MgO:Al_2O_3:SiO_2$ given in Figure 12 shows the same general condition. If a mass of sillimanite were immersed in molten $MgSiO_3$ and Mg_2SiO_4 in equal parts, a layer around the inclusion, which might have the bulk composition 75 per cent sillimanite, 25 per cent the above mixture, would consist at higher temperatures of corundum and liquid; at lower temperatures, of

sillimanite, spinel, and liquid; and at still lower temperatures, of sillimanite, spinel, and cordierite.

It should be realized that these conditions we have pictured as occurring about sillimanite inclusions are transient states. We may deduce from an equilibrium diagram the condition of a certain layer about an inclusion, but the system as a whole is not in equilibrium

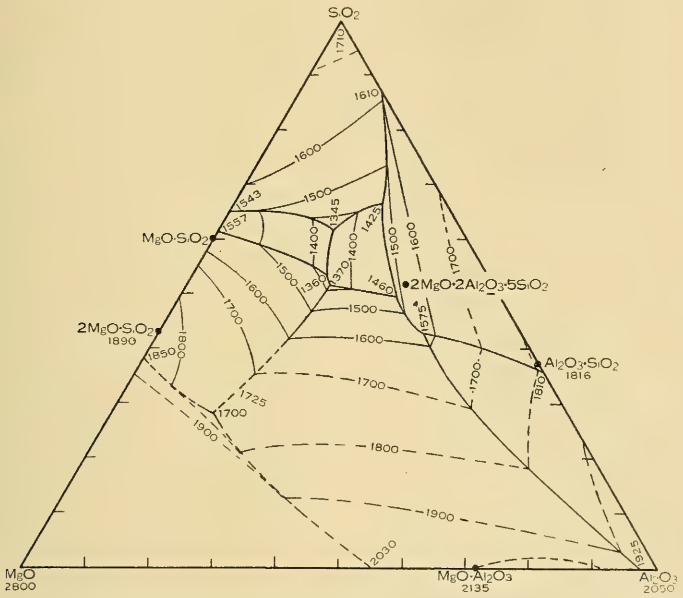


FIG. 12.—Equilibrium diagram of the system MgO-Al_2O_3-SiO_2. (After Rankin and Merwin.)

since there are composition gradients about these inclusions. Nevertheless this changing state might become fixed and be revealed as a result of complete consolidation of the mass.

The actual magma by which the schist inclusions were attacked may be regarded as showing the combined effects of the anorthite liquid and the magnesian liquid of the experimental systems. It is true the magma did not correspond definitely with any such mixture of anorthite and magnesian silicate, but it was closely related, consisting mainly of plagioclase and magnesian silicates, and its effect on sillimanite-rich inclusions might reasonably be similar.

The effect was indeed very similar, for the sillimanite-rich inclusions are found to be changed by the magma to masses rich in corundum, spinel, and cordierite, with other related minerals. It is inclusions that have been thus affected that constitute the emery deposits. They represent the reaction between the magma and inclusions arrested midway. No doubt many inclusions completely disappeared, becoming an integral part of the igneous rock in virtue of reactions involving adjustment of composition of existing phases. (See p. 549.) The feldspathic emery and the noritic emery may, from this point of view, be regarded as inclusions approaching their final disappearance.

These transient states in which inclusions may be very rich in certain substances are no doubt of some importance in differentiation. Localized masses in process of reaction with the general mass may move, say in response to gravity, and their accumulation may give rise to bodies rich in minerals formed during the reactions. All up and down the Appalachian Mountain system of Eastern North America there are intrusive masses showing ultrabasic differentiates with dunite as the extreme and with associated peridotites and pyroxenites frequently rich in rhombic pyroxene, saxonite, websterite and enstatolite itself. These are usually, perhaps always, intrusive into slates and mica schists that were originally aluminous sediments, the Farnham slates of Quebec, the Savoy and Rowe schists of New England, the Manhattan of New York, the Wissahickon of Pennsylvania and Maryland, and the Carolina gneiss of the Southern States. These have perhaps had an important influence in emphasizing differentiates of the types mentioned above. There are, moreover, corundum deposits, either as emery or in purer forms, in frequent association with these ultra-basic rocks and in some cases the origin and accumulation of corundum may be referred to processes outlined above. Gordon has demonstrated a different origin for some of them,[1] but the action here described seems unquestionable for the Cortlandt emery and the gangue minerals of some of the Carolina deposits strongly suggest a similar origin. These gangue minerals are basic plagioclase, sillimanite and

[1] Formation by reaction between pegmatite and serpentine. S. G. Gordon, *Proc. Acad. Natural Sci. Philadelphia*, Part I (1921), p. 169.

cyanite. That such minerals together with corundum could form from basic magnesian rocks by simple differentiation is very doubtful.[1]

The progressively selective nature of the reaction between magma and inclusions that is shown by these Cortlandt examples and the theoretical considerations discussed in connection therewith demonstrate that a former statement of mine that "the formation of an obviously hybrid rock should, apparently, be the normal result of assimilation"[2] is erroneous and that Daly's objections thereto are justified.[3] Daly's objections are based on considerations other than those raised above and refer rather to the changes that may occur in a *superheated* magma during the slow diffusion into it of xenolithic material. We may recall here that the reactions herein described are those that are to be expected between *saturated* magma and schist inclusions. The fact that the reactions are selective in a way that matches the expectation may presumably be regarded as evidence that the magma was saturated.

Recognition of the probable saturated condition of the magma is of importance because it shows that there could not have been formed, at any time, a liquid whose composition was simply the sum of that of the original magma and the inclusions. Even that portion of the foreign matter which becomes a part of the liquid does so only by precipitating phases with which the magma is saturated and must itself be of a composition toward which the liquid may go spontaneously by fractional crystallization. So in the case of the Cortlandt series various diorites, some syenite and a considerable amount of granite (first recognized by Berkey as a part of the series)[4] were formed by differentiation as they would have been under the same conditions without reaction with slate material, though presumably the amount of "acid" differentiates was augmented by its addition.

Another suggestion concerning the incorporation of slaty rocks in basic magmas may be made at this point. In the neighboring

[1] See Rankin and Merwin, "The Ternary System MgO-Al_2O_3-SiO_2," *Amer. Jour. Sci.*, Vol. XLV (1918), p. 325.

[2] N. L. Bowen, *Jour. Geol.*, Supplement to Vol. XXIII (1915), p. 85.

[3] R. A. Daly, *Jour. Geol.*, Vol. XXIII (1918), p. 126.

[4] C. P. Berkey, *Science*, Vol. XXVIII (1908), p. 575.

state of Connecticut there occurs a group of rocks showing a striking resemblance to the Cortlandt series.[1] With these are associated nickeliferous sulphide deposits of magmatic origin.[2] This association is highly characteristic, examples of norite and related rocks with nickeliferous sulphides being too familiar to require special enumeration. It seems possible that the incorporation of slaty rocks may be of importance not only in connection with the formation of norite but also of the sulphide deposits, for slaty rocks are very commonly pyritic. At first thought it might seem that the addition of pyrite to a basic magma would not account for the separation from it of the sulphides commonly found in such nickel deposits. However, if pyrite, say as globules of immiscible liquid, remained long immersed in a basic magma it would be subject to the same kind of modification of composition as is any other foreign matter. In short, it would have its composition changed to such sulphides as are particularly insoluble[3] in such magma. Thus if iron, nickel, copper sulphides could separate from such a magma by normal processes, were they present in sufficient amount, then immersed pyrite would be changed to just such iron, nickel, copper sulphides. It seems worthy of consideration, therefore, that the sulphide deposits associated with norites may often be *reconstituted* deposits having their ultimate origin in the incorporation of pyritic slates. Indeed at Sohland and Schweidrich on the Saxony-Bohemia border typical ores of this kind are intimately associated with masses representing what we have termed the transient state of slate inclusions, that is, with masses rich in spinel, sillimanite and corundum.[4]

In connection with the formation of norite and perhaps of sulphide deposits, through the influence of absorbed slates, it should be realized that the action is probably an emphasis upon normal processes. It may very well be, however, that if there were no argillaceous sediments norites would be of much rarer occurrence than they are.

[1] W. H. Hobbs, *Festschrift v. H. Rosenbusch.*, pp. 25–48. Stuttgart, 1906.

[2] Ernest Howe, *Economic Geol.*, Vol. X (1915), p. 330.

[3] Probably as liquid, i.e., immiscible.

[4] Beyschlag, Vogt, Krusch, Truscott, *Ore Deposits,* Vol. I, p. 299, London, 1914.

THE ACTION OF BASIC MAGMAS ON SILICEOUS SEDIMENTS

A number of examples of argillaceous quartzites are known that have been invaded by basaltic magma and in which it is believed by some investigators that absorption of the siliceous sediments by the magma has occurred. Two carefully studied examples are the Pigeon Point sill of Minnesota[1] and the Moyie sills of British Columbia.[2] Such quartzites may again be regarded as consisting of material belonging to a later stage of the reaction series than basaltic magma, together with a certain surplus. The former, corresponding in composition with some acid igneous rock, should be capable of becoming part of the liquid magma by precipitating its heat equivalent of the phases with which the magma is saturated. There is no theoretical objection, therefore, to the belief that a certain amount of the inclusions could be incorporated in this manner even though the magma is saturated. It should be borne in mind, however, that the material that can thus become a part of the liquid must be of a composition toward which the magma could change spontaneously by fractional crystallization. Once incorporated, it requires, to produce the acid differentiates that were there formed, the same conditions of crystallization as would have produced an acid differentiate from the uncontaminated magma. In all of these examples the normal course of differentiation is the primary consideration. The extent to which incorporated material contributed to the bulk of the acid differentiate may not have been important in these small bodies even though there is plain evidence of incorporation.

At both localities mentioned evidence of some incorporation is unquestionable. About inclusions of the sedimentary rocks reaction rims of a granitic nature have been formed. We have seen on page 529 that the reaction should emphasize, in the liquid around the inclusion, material belonging to a later stage of the reaction series (i.e., toward which the magma can crystallize), and this should not be intermediate in composition between magma and inclusion. Corresponding with this deduction we find that the rims about the xeno-

[1] W. S. Bayley, *U.S. Geol. Survey, Bull. 109*. R. A. Daly, *Amer. Jour. Sci.*, Vol. XLIII (1917), p. 423.

[2] R. A. Daly, *Geol. Survey Can., Mem. 38*, p. 226. S. J. Schofield, *Geol. Survey Can., Museum Bull. No. 2*.

liths are not simply melted xenolith but essentially normal igneous material of a late stage of the reaction series. The reaction-rim stage is a temporary one except in so far as it may be preserved about some inclusions by exhaustion of the magma. Others disappear entirely by diffusion of the rim material into the magma and distribution (with possible precipitating effects) of any surplus material. Thus the liquid is pushed onward in the reaction series, not only through addition of the rim material, but also because this necessitates some precipitation of the early-formed minerals from the basic magma. Further fractional crystallization may therefore give differentiates identical with, or closely related to, the reaction-rim material, but normal differentiation might have given it also.

Inclusions of some acid sediments, richly charged with volatile substances (mainly water) and immersed in a basic magma under conditions permitting their retention of this volatile matter, might, theoretically, be converted to liquid in toto. Actually, few inclusions show any such effect, from which fact it may be assumed that the conditions mentioned are seldom realized. That the reaction effect discussed is the important one quantitatively seems unquestionable.

EFFECTS OF GRANITIC MAGMA ON INCLUSIONS OF SEDIMENTARY ORIGIN

In discussing the reaction of magmas with inclusions we have, in the case of basaltic magma, made some reference to the superheated condition. Daly points to basaltic magma as the heat bringer, and has presented evidence that such magma enters into igneous-rock economy on a different basis from all other magmas.[1] If this be true, and his reasons seem to me convincing, basaltic magma is the one magma that may, presumably, be assumed to have superheat on some occasions. All other magmas, whether they may be formed by differentiation of basaltic magma or by differentiation of syntectic magma must usually be saturated, unless it be that locally, at volcanic vents, a special source of heat is available. This possibility has little quantitative petrogenic significance and it is perhaps a realization of the commonly saturated condition of other

[1] R. A. Daly, *Igneous Rocks and Their Origin*, p. 458.

magmas that has led Daly to adopt basaltic magma as his solvent. Thus all of Daly's syntectics are of *basaltic magma* with various types of foreign matter. We have already seen, however, that the saturated condition is no bar to a *reaction* between magma and inclusions. This fact is as true of intermediate magmas as of any others and the same principles apply to them.

If the foreign material belongs to an earlier stage of the reaction series the tendency is to make it over into those phases with which the magma is saturated and to precipitate a further amount of these phases from the magma itself. If the foreign material belongs to a later stage of the reaction series it tends to become a part of the liquid by precipitating phases with which the magma is saturated.

Sediments do not belong in the reaction series at all and certain types of sediments contain material belonging in both the above classes and both effects may be obtained. Our chief purpose here is to consider principles, and it seems unnecessary, therefore, to discuss individually the action of various intermediate magmas on various foreign inclusions.

It is perhaps desirable, however, to discuss the action of granitic magma on sediments, its action on igneous inclusions having already been described. For the reason mentioned above, only saturated granitic magma will be considered. Quartzites and slaty rocks offer no special problem. They are readily transformed into phases with which the granite is saturated, an action that any magma will accomplish in so far as the composition of the sediment permits. The conversion of inclusions of such rocks by granitic magma into masses of quartz, feldspars, and micas, in varying proportions, should therefore be the result. A certain amount of mechanical disintegration might cause the strewing about of these products in such a way as to make them an integral part of the mass but there should be no solution. Intermediate steps might see the formation of such minerals as sillimanite, garnet, and others characteristic of contact rocks, but these should be temporary or should survive only because of exhaustion of the liquid.

The kind of effect that sillimanite produces by reaction with basic magmas, namely, the precipitation of orthopyroxene and basic plagioclase is not to be expected in granitic magma. Rather should

we expect precipitation of the micas in acid magmas, and formation of orthopyroxene in such magmas is to be referred to other causes than that proposed by Evans[1] and here adopted for basic rocks.

When we turn to the case of carbonate rocks we find that the reaction with granitic magma is of a different nature. It is often observed that wall rock and inclusions of carbonates are altered to silicate minerals.[2] It has been assumed by some investigators, therefore, that silica has been subtracted from the granitic liquid and that this may occur to such an extent that some of the feldspar molecules are transformed into the less siliceous, feldspathoid molecules with consequent formation of alkaline rocks. This assumed action is said by certain writers to be in agreement with Daly's theory of the origin of alkaline rocks. We have seen above, however, that Daly assumes that superheated basaltic magma is the starting point for all his syntectic magmas and that alkaline rocks are differentiates of some of these syntectics, principally those formed with carbonate rocks. We have pointed out on a preceding page that, if adequately superheated basalt were available, it might form, by solution of carbonates, a melilite basalt and, given the latter, alkaline differentiates seem not impossible and so indeed some alkaline rocks may be formed. Not all alkaline rocks can be so explained, for much nephelite syenite shows intimate genetic relations with granites and on Daly's general theory the original basaltic magma would require to be silicated by solution of acid material to form the granite and desilicated by solution of carbonates to form the nephelite syenite. That the differentiates should show evidence of both seems out of the question. The solution of foreign matter must result in either desilication or silication according to the preponderance of one or the other type of foreign matter and subsequent differentiates should be in conformance with one or the other but not both.

This brings us back to the question whether a nephelite syenite, intimately associated with a granite, could have been formed as a result of desilication of the granite by carbonate inclusions, that is,

[1] J. W. Evans, *Quar. Jour. Geol. Soc.*, Vol. XLVIII (1921), p. 133.

[2] For example in the large-scale production of amphibolites in the Haliburton-Bancroft area. Adams and Barlow, *Can. Geol. Surv., Mem. No. 6* (1910).

back to the question of the effect of granitic magma on carbonate inclusions.

We have noted the silication of the inclusions and the consequent supposed desilication of the liquid. In discussing investigated systems we have already found, however, that saturated liquids cannot have ingredients subtracted from them at random without causing precipitation of other ingredients so that the effect on the liquid is not mere impoverishment in the ingredient subtracted. This may perhaps be made clear by a simple example. If we had a solution of salt at $-20°$ C, and any hypothetical substance was placed in the solution that withdrew the salt from it, the result would not be simply the leaving behind of liquid water. The reason is simply that liquid water cannot exist at $-20°$ C and the actual result would be that, as each small amount of salt was removed, a small amount of ice would form and, when all the salt was withdrawn, all of the water would have become ice. For the maintenance of liquidity, the salt and the water are necessary each to the other. And so it must be with a saturated granitic solution. Remove the silica from it and other substances must be precipitated. Now the reaction of granitic magma with inclusions of carbonate rock is not a simple addition of silica to the latter but usually other substances are added as well, these being such as to convert the inclusions ultimately into diopsidic pyroxene or hornblende. The reason for the formation of these phases is that they belong at an earlier stage of the reaction series than the biotite with which granitic magma is normally saturated. The subtraction of the substances necessary to produce these minerals must, for reasons outlined above, cause concomitant precipitation of the other phases normally formed from granitic magma, principally feldspar. Thus the action described must bring about an exhaustion of the liquid by causing precipitation. There seems to be no reason for believing that it could first exhaust the free silica, leaving a feldspar-rich *liquid*, then, upon further action, cause removal of some of the silica from the feldspar *liquid* leaving a *liquid* containing feldspathoid molecules.

A reaction of the kind described, that is, a using up of some silica to form diopside with the consequent precipitation of feldspar and quartz, would seem to me to be the mode of formation of the

diopside-bearing variety of the Beckett gneiss, of which Eskola has written a description and interpretation.[1] I visited the localities with Dr. Eskola, and in my opinion the transformation of the solid dolomite into solid diopside with its effect upon the granitic liquid was the dominant action in the production of the types of gneisses there found, and of their banding, rather than actual solution of the dolomite or skarn in the granite and subsequent differentiation of the syntectic liquid. It must be admitted, however, that the solubility of $CaCO_3$ in magmas is probably greater than that of CaO and that under conditions permitting the retention of CO_2 an amount of limestone might be dissolved greater than that suggested by the reaction effects already discussed. The usual free conversion of limestone into silicates indicates, however, that it is not commonly so dissolved.

The formation of basic silicates, without the production of feldspathoids, seems to be the ordinary result of the action of granitic magma on limestone inclusions. Thus, in the granitic portions of the Bushveldt laccolith altered limestone inclusions are surrounded by a halo of dioritic material, but not by alkaline rock.[2] Other examples might be given; in fact, the ordinary effects of granite on limestone seem to be those we have deduced for a saturated granitic magma.

In one locality the alkaline facies of the Bushveldt complex is, it is true, intimately associated with a mass of limestone, and as a result of a study of this locality Shand has concluded that there is some connection between the production of the feldspathoids and the desilicating action of the magma. Apparently Shand does not believe that the entire production of nephelite is due to this action but rather that a nephelite syenite magma becomes ijolite by desilication.[3] This is a quite different matter from the production of the original nephelite syenite magma by such desilication. No theoretical objection can be raised against the belief that interaction with limestone could reduce the amount of feldspar and increase the

[1] P. Eskola, *Jour. Geol.*, Vol. XXX (1922), pp. 265–94.

[2] Oral communication. Professor Brouwer.

[3] S. J. Shand, *Trans. Geol. Soc. South Africa*, Vol. XXII (1921), pp. 144–46.

amount of feldspathoid in a magma already capable of precipitating both of these. Such adjustment of the relative amounts of minerals we have found to be a common effect of inclusions.

It is probable that alkaline rocks are ordinarily produced by crystallization differentiation from subalkaline magmas. A possible method in the case of a leucite-bearing rock has been demonstrated by Morey and Bowen, who show that a liquid of the composition of orthoclase or even one with a moderate excess of silica over the amount necessary to form orthoclase will precipitate leucite as the first-formed crystals.[1] If an orthoclase-rich liquid came into being by fractional crystallization of a more basic magma it might, under the appropriate conditions, show the above effect. The fact that the excess silica must be no more than a small amount should be noted, for this fact renders it possible that limestone may, in spite of the many objections that have been raised above, have some influence in promoting the formation of alkaline rocks. The influence is, however, an emphasizing of a normal tendency rather than a fundamental necessity. This we have found to be a general rule in connection with the effects of inclusions. If the differentiation of the magma which gave rise to the orthoclase-rich liquid took place in the presence of a supply of limestone inclusions this would tend to reduce to a minimum any excess silica that might otherwise be associated with the orthoclase. Thus the normal tendency of the orthoclase to break down into leucite under the proper conditions would be free to assert itself. We may therefore accept the possibility that reaction with limestone may emphasize the tendency toward the formation of an alkaline differentiate, though it is not essential to it. Other factors, such as the failure of olivine to form at an early stage in the magma's history, or the free resorption of such olivine as does form, may also assure a low excess of silica at a late stage with likelihood of the separation of feldspathoids. The tendency of feldspathoid to separate under these conditions has been demonstrated as yet only for leucite, but the frequent intimate association of leucitic and nephelitic rocks renders it probable that the factors governing the formation of the nephelitic rocks are not unrelated.

[1] *Amer. Jour. Sci.*, Vol. IV (1922), pp. 1–21.

DEDUCTIONS TO BE COMPARED WITH OBSERVED RESULTS

Throughout the foregoing study of the reactions between inclusions and magma, attention has been directed mainly to its theoretical aspects, that is, to deducing from equilibrium considerations what reactions should occur, together with the effects of these upon the further crystallization of the magma. All of these deductions can be put to the test by observation of what has actually occurred, in particular by a study of the reaction rims formed about inclusions. It should not be expected that each inclusion will tell the whole story, but a general study of inclusions should do so. Not all the differentiates that might later form from the hybrid mass need be shown by the reaction rims, but certainly there should be formed some whose relationship to these possible later differentiates is established by their frequent association in many areas.

In some instances examples have been cited which appear to show that the expected reactions do occur. Such are the formation of granitic reaction rims by the action of basaltic magma on acidic rocks, the making of basic inclusions into biotite-rich masses by granitic magma, and others. The formation of alkaline rocks by the action of ordinary magmas on limestones is, at present, incapable of support on the above grounds. No example is known where inclusions of limestone, contained in an ordinary rock, are surrounded by reaction rims of feldspathoid-bearing rock. It is true that limestones and alkaline rocks are often intimately associated, but there is no assurance that the magma was not already an alkaline magma before it acquired this association. As we have already pointed out, this appears to be the conclusion that Shand reaches concerning the Sekukuniland occurrence, though he favors also the conception that the limestone emphasized its alkaline nature.

In the Fen area of Norway, one of the newer areas to which the limestone-syntectic hypothesis has been applied, there is a very striking association of alkaline rocks and carbonate rocks.[1] However, nothing there displayed demonstrates a change of subalkaline magma to alkaline magma through the influence of the carbonate

[1] Cf. W. C. Brögger, "Die Eruptivgesteine des Kristianiagebietes IV," *Vid. Selsk. Skr. I. Mat. Naturv. Klasse* (1920).

rock. No support in the way of reaction rims of the appropriate kind has yet been found for the limestone-syntectic hypothesis. Some such support is desirable before the hypothesis can be accepted, even though there is reason to believe, as pointed out above, that the presence of limestone might emphasize the normal tendency of magmas to give an alkaline differentiate.

SUMMARY

The question whether magmas can dissolve large quantities of foreign inclusions is one that has been much debated by petrologists. Some have claimed great powers for magmas in this respect and in addition have assigned a dominant rôle in the production of differentiation to such solution of foreign matter. Others have insisted that magmas have not the necessary heat content to enable them to give significant effects of this kind. A study of some simple equilibrium diagrams, with the object of determining the heat effects connected with solution, gives every reason for believing that the effect is a large absorption of heat, usually of the order of magnitude of the latent heat of melting. For simple solution, then, it is unquestionable that large amounts of heat will be required.

Those who believe in the actuality of the solution of considerable amounts of foreign matter in magmas have usually realized this fact and have sought a source of the heat in magmatic superheat of great amount, that is, in a large excess of temperature of the magma above its crystallization range. A study of the probabilities of the case and of the usual effects of magmas upon inclusions leaves little reason for believing that magmas can ordinarily have any considerable superheat.

Unquestionably, then, the observed effects of magmas upon inclusions are usually to be referred to an action other than the direct solution of inclusions in superheated magma. An application of the conception of the reaction series to the solution of the problem affords an explanation of the effects of magmas, even though saturated. Certain principles governing the effects of liquid upon inclusions belonging to reaction series can be developed by studying the equilibrium diagrams of systems involving both continuous and discontinuous reaction series. In this manner it can be decided

definitely that a liquid saturated with a certain member of a reaction series is effectively supersaturated with all preceding members of that series. It cannot dissolve such members but can only react with them to convert them into the members with which it is saturated. The reaction is not a simple subtraction from the liquid of the material necessary for this transformation, but some precipitation from the liquid itself is involved and the liquid ordinarily maintains its position on the same saturation surface. The products of crystallization from the liquid and the possible course of fractional crystallization are thus unaffected.

On the other hand, a liquid saturated with a certain member of a reaction series is unsaturated with all subsequent members of the series. Inclusions consisting of these later members can become a part of the liquid by a sort of reactive solution, the heat of solution of inclusions being supplied by the precipitation of their heat equivalent of the member of the series with which the liquid is saturated. It should be noted that the material that can by this reactive process become a part of the liquid must consist of a later member of the reaction series, that is, must be material toward which the liquid could pass spontaneously by fractional crystallization. The net effect upon the liquid is, then, to push it onward upon its normal course.

In Table II the products of crystallization of subalkaline magmas are arranged as reaction series, as definitely as may be in such complex series. The action of magmas upon foreign inclusions of igneous origin may be deduced from this arrangement of the crystalline products as series by application of the principles developed from the above study of simple systems. Thus we find that a granitic magma saturated with biotite cannot dissolve olivine, pyroxene, or amphibole, but can only react with them to convert them into biotite, the phase with which it is saturated. Or, stated more generally, no saturated magma can dissolve inclusions consisting of minerals belonging to an earlier stage of the reaction series (usually more basic).

Saturated basic magma, on the other hand, will react with inclusions belonging to a later stage of the reaction series (more acidic), the reaction being of such a nature that the inclusions become a part

of the liquid by precipitating their heat equivalent of the phases with which the magma is saturated (basic minerals). The inclusions, it should be noted, must be of a composition toward which the liquid could pass spontaneously by fractional crystallization. Thus saturated basaltic magma can dissolve granitic inclusions by precipitating basic minerals and the granitic material passing into solution then becomes a contribution to the normal granitic differentiate that may form by fractional crystallization if the conditions are appropriate.

The behavior of inclusions of sedimentary origin is more complicated since sedimentary material does not belong in the reaction series. A consideration of the extent and nature of the variation of composition possible in the crystalline phases formed from a magma shows that the incorporation of considerable amounts of sedimentary material would ordinarily bring about merely an adjustment in the composition and relative proportions of existing phases. As a result of the non-appearance of new phases, the general course of fractional crystallization is unaffected. In general, the adjustment noted takes place through precipitation of the phases with which the magma is saturated. As an example it may be stated that the addition of highly aluminous sediments to basic magma should bring about the formation of anorthite and enstatite molecules at the expense of diopside molecules and should therefore cause the precipitation of crystals rich in anorthite and enstatite. Such action may have been important in the formation of many norites. The foreign material becomes a part of the general mass as a result of reaction and precipitation rather than by simple solution.

The Cortlandt series of New York, with its inclusions, affords an illustration of the behavior of aluminous sediments in basic magma. Such sediments may be regarded as consisting in part of material corresponding in composition with igneous material late in the reaction series, together with a certain excess, which is highly aluminous. The former may become a part of the liquid by the method of reactive solution already described. There results the piling-up of the highly aluminous excess in the inclusions, with formation of such minerals as sillimanite. Moreover, as a consequence of what may be somewhat loosely called the instability of sillimanite in contact

with liquid rich in anorthite or magnesian silicates, alumina is set free as corundum. This condition is transient, however, and even these residues from the inclusions may become a part of the general mass as a result of the reactive precipitation noted above. The net result is the formation of noritic material with an increase in amount of the acidic differentiate normally possible.

The addition of limestone to basaltic magma may perhaps give rise to a liquid capable of precipitating melilite in some cases and from such a liquid it is possible that some alkaline rocks may form by further differentiation. It does not seem possible that limestone inclusions can desilicate a granitic magma in such a way as to give rise to a liquid capable of precipitating feldspathoids. However, if limestone inclusions were present during the differentiation of the more basic liquid from which the granitic liquid may have formed, the presence of such inclusions might reduce the amount of free silica associated with the alkaline feldspar in this liquid to such an extent that the normal tendency of orthoclase to break down into leucite would manifest itself. Thus rocks bearing leucite, and possibly other feldspathoids, might form, but influences prevailing during early stages of differentiation, other than the presence of foreign matter such as limestone, may likewise lead to the formation of leucite at a late stage.

In conclusion, it may be stated, therefore, that magmas may incorporate considerable quantities of foreign inclusions, both by the method of reactive solution and by reactive precipitation, and such action may have been important in connection with the production of certain individual masses. Thus some norites may have been produced as a result of the reactions discussed above, some granites may have had their mass augmented by reactive solution of granitic inclusions in the magma from which they differentiated, some alkaline rocks may have been formed as a result of the presence of limestone inclusions in the liquid from which they differentiated. All of these actions are, however, an emphasizing of normal processes possible in the absence of foreign matter. It is doubtful whether the presence of foreign matter is ever essential to the production of any particular type of differentiate.

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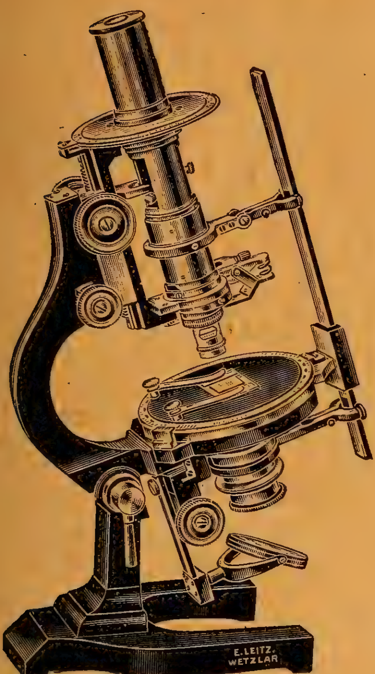

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THE NEPHELITE SYENITE AND NEPHELITE PORPHYRY OF BEEMERVILLE, NEW JERSEY

M. AUROUSSEAU AND HENRY S. WASHINGTON
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OUTLINE

INTRODUCTION

During the earlier geological survey of New Jersey many outcrops of igneous rocks, mainly dykes, were mapped and recorded in the state reports without particular description. These rocks are nearly all located in Sussex County, and, owing to the small size of most of the outcrops, their scattered nature, the maturity of the topography, and the extent of weathering of the rocks themselves, their interesting nature has only been recognized gradually, though the first record of the largest mass dates back to 1868.

Through the work of Emerson, Kemp, and Wolff these rocks are now widely known and are regarded in the local sense as a suite of genetically connected alkalic intrusions, and more generally as

showing affinity with the rocks of a dominantly sodic zone or comagmatic region which finds expression in the eastern United States from New England to Texas.[1]

The large mass of nephelite syenite situated to the northwest of Beemerville was first described in detail by Emerson, who recognized its true character and described it microscopically. He believed the mass to be a large dyke.[2] Emerson also described, under the name of mica-diabase, the series of dykes penetrating the ore-bodies at the Buckwheat Field at Franklin Furnace.[3]

Kemp examined the mass known as Rutan's Hill, which forms a prominent landmark east of the northern end of the main mass of nephelite syenite at Beemerville, and described it as a boss of porphyrite, giving two analyses of the rock, and one of the biotite isolated from it.[4] He also recognized the nature of a number of similar "bosses" to the southeast of the main mass, south of Beemerville and Plumbstock. On a more detailed investigation Kemp mapped and described the main mass and its immediate satellites, demonstrating clearly the inhomogeneity of the Beemerville nephelite syenite and proving the occurrence of a nephelite porphyry, probably as a dyke, within it. Here also he showed that the satellitic bosses are basic alkalic rocks, allied to the ouachitites and fourchites. He provided two analyses of different facies of the nephelite syenite and one of the nephelite porphyry.[5] These investigations established the fact that the Beemerville mass and its associates resemble the rocks of the Magnet Cove complex, Arkansas.

Kemp next examined a basic dyke two miles northwest of Hamburg, and from microscopical investigation, and the analysis of certain pseudomorphous spheroids which it exhibited, he offered the tentative suggestion that the rock was a leucite tephrite, and concluded that it was related to the Beemerville nephelite syenite.[6]

[1] H. S. Washington, *Jour. Franklin Inst.*, CXC (1920), p. 796.

[2] B. K. Emerson, *Amer. Jour. Sci.*, XXIII (1882), p. 302.

[3] *Ibid.*, p. 376.

[4] J. F. Kemp, *Amer. Jour. Sci.*, XXXVIII (1889), p. 130.

[5] J. F. Kemp, *Trans. N.Y. Acad. Sci.*, XI (1892), p. 60.

[6] J. F. Kemp, *Amer. Jour. Sci.*, XLV (1893), p. 303.

Kemp's material was studied by Hussak, who had no hesitation in terming the rock a leucite tephrite, and considered that the spheroidal pseudomorphs were pseudoleucite, or were at any rate pseudomorphs after leucite.[1] Kemp then visited some newly exposed dykes at Rudeville and obtained material which provided definite proof of the existence of leucite, and came to the conclusion that the "mica-diabase" dykes of Rudeville, Franklin Furnace, and the Hamburg dyke are all related to the Beemerville mass.[2] Kemp's papers are illustrated with useful locality maps, but the analyses given are all incomplete and inadequate.

A complete petrological description of the nephelite syenite of Beemerville and the large dyke at Franklin Furnace, together with good, though incomplete, analyses, is given by Iddings, who recognized the Franklin Furnace dyke to be a minette.[3]

In 1899 Ransome described a small occurrence of nephelite syenite, mica syenite, hornblende syenite, and hornblende granite, associated with Mesozoic gabbro, at Brookville, in Hunterdon County, New Jersey, sixty miles west of south from Beemerville. The relations of these rocks to the gabbro were not clearly ascertained, and they were regarded by Ransome as inclusions, though he considered the possibility of an intrusive relation.[4] Our colleague, Dr. N. L. Bowen, has collected specimens from this locality which suggest differentiation of the nephelite syenite and, on a small scale, an intrusive relation toward the gabbro.

In 1902 Wolff described an undoubted leucite tinguaite dyke, which cuts the Beemerville nephelite syenite mass near its southern end, giving a detailed account of the pseudoleucite, and a good and complete analysis of the rock. This is the most satisfactory existing analysis of any rock from the alkalic series of Sussex County.[5] Finally, in 1908 Wolff provided a co-ordinated description of the igneous rocks of Sussex County,[6] in which he points out that the same

[1] E. Hussak, *Neues Jahrbuch*, II (1892), p. 153.

[2] J. F. Kemp, *Amer. Jour. Sci.*, XLVII (1894), p. 339.

[3] J. P. Iddings, *U.S. Geol. Surv., Bull. 150* (1898), pp. 209 and 236.

[4] F. L. Ransome, *Amer. Jour. Sci.*, VIII (1899), p. 417.

[5] J. E. Wolff, *Bull. Mus. Comp. Zoöl. Harvard*, XXXVIII (1902), p. 273.

[6] J. E. Wolff, *Geol. Atlas, New Jersey*, Franklin Furnace folio (1908), p. 12.

pyroxene, a zoned aegirite-augite, and large crystals of titanite and biotite characterize nearly all the rocks of the series, and that the main nephelite syenite mass of Beemerville, with its transgressive dykes of nephelite porphyry and leucite tinguaite, has a definite relation to the disposition of other rocks of the series. Close to it, to the east and south, are the bosslike or necklike ouachitite breccias; farther to the southeast is a zone of nephelite syenite and bostonite dykes, which, like the main mass, are concordant with the bedding of the intruded series (the Ordovician Martinsburg shale); finally, at some distance to the southeast, are the lamprophyric dykes, which are disposed radially toward the Beemerville mass, intruding the Ordovician Kittatinny limestone and the pre-Cambrian Franklin limestone. Wolff concludes that the alkalic rocks are post-Devonian in age and probably much later.

THE NEPHELITE SYENITE OF THE BEEMERVILLE MASS

The main mass of nephelite syenite forms a long, narrow intrusion of elliptical outcrop, lying between the Silurian Shawangunk conglomerate and the Ordovician Martinsburg shale, at the foot of the Kittatinny Ridge, the southern extremity of the mass being two miles to the northwest of Beemerville. It is most easily accessible from the town of Sussex (formerly called Deckertown, and referred to by that name by Emerson and Kemp).

The formal relationships of the mass are obscure. Both Emerson and Kemp regarded it as a large dyke, but Wolff is inclined to regard it as a sill, or an irregular, flat laccolithic mass. Washington visited the locality in 1901 in company with Professors Kemp and Brögger, and is in agreement with Wolff's opinion. It was examined by Aurousseau in the summer of 1921, with special regard to this point, but no evidence of a decisive nature is obtainable on the ground. As the mass has been studied by a number of competent geologists at intervals over a long period of time, it is improbable that any fuller information will be forthcoming, the outcrops being poor and the contacts obscured by thick soil and drift. In particular, no variations of dip are to be observed in the massive Shawangunk conglomerate which overlies the mass. To our minds the occurrence of the body (which can hardly be younger than

early Tertiary and is probably much older) at the junction of the Shawangunk conglomerate and the Martinsburg shale, is critical, and, taken in conjunction with the fact that long, narrow intrusions of nephelite syenite and bostonite lie parallel to the bedding of the Martinsburg shale farther to the east, inclines us to the opinion that the Beemerville mass is a lenticular sill, or a flat laccolith.

The nephelite syenite is a somewhat basic foyaite, of the "foyaite range" as recently defined in the classification of the nephelite syenite family proposed by Shand.[1] It is very variable along the mass and, although the bulk of the exposure is a fairly constant foyaite of the Magnet Cove, Arkansas, or the Umptek type, it grades locally into other facies, which are often more basic than the main mass. Ditroitic and ijolitic modifications may be collected, and especially along the eastern border it becomes foliated, or lujavritic, in character. Near the center of the exposure, small, local facies with abundant titanite may be found. These variations have been admirably described by Emerson and by Kemp. Kemp's description may be quoted to illustrate this point:

> The dike varies considerably along its course. The typical elaeolite-syenite forms the northern third and the southern extremity, but between these points its character changes. Near the southern part of the middle third elaeolite-porphyry appears, and forms a most beautiful example of this rock. It may come from dikes, as no actual exposures are available. Further south a basic holocrystalline rock comes in which is exposed in place; and, as subsequently shown, contains less silica and more biotite than the typical syenite. But on the extreme south where the highway crosses the dike, the rock is much like that on the north. It is, however, greatly decomposed, and fresh, firm, pieces are hard to find.[2]

The variation, even of what appears to be the predominant rock, is well shown by comparing the analyses by Eakins and Aurousseau (Table I). The Martinsburg shale, along the eastern contact, has been metamorphosed to a hornstone, the aureole being narrow.

To the very complete petrographic description of the normal rock, given by Iddings, we have little to add. One slight correction is necessary. The mineral identified as sodalite belongs to the hauynite-noselite series, as is indicated by the analysis here given.

[1] S. J. Shand, *Trans. Geol. Soc. South Africa*, XXIV (1921), p. 117.

[2] J. F. Kemp, *Trans. N.Y. Acad. Sci.*, XI (1892), p. 64.

The most noteworthy chemical characters of the nephelite syenite are its low silica percentage, the approximate equality in amount of soda and potash, the high content of titanium and zirconium, and the comparatively large amount of SO_3 as compared with chlorine. Though it undoubtedly belongs to the highly sodic

TABLE I

	I	II	III	IV	V	
SiO_2	47.19	53.56	53.09	52.25	Z	0.18
Al_2O_3	23.01	24.43	21.16	22.24	Or	33.08
Fe_3O_2	3.11	2.19	1.89	2.42	An	6.39
FeO	2.23	1.22	2.04	1.98	Lc	11.99
MgO	1.07	0.31	0.32	0.96	Ne	32.66
CaO	2.93	1.24	3.30	1.54	Th	0.71
Na_2O	7.97	6.48	6.86	9.78	Nc	0.95
K_2O	8.23	9.50	8.42	6.13	Di	4.32
H_2O+	0.55	0.93	1.13	0.73	Ol	0.98
H_2O-	0.04		0.24		Mt	1.39
CO_2	0.38	....	0.82	....	Il	4.10
TiO_2	2.16	....	0.11	0.60	Hm	2.08
ZrO_2	0.13	....	0.04	....	Ap	1.01
P_2O_5	0.39	....	0.15	0.53	Water	0.59
SO_3	0.45	....	None	....	....	....
Cl	0.01	....	0.02	....	....	....
F	p.n.d.	....	....	....	....	....
S	....	....	0.08	....	....	....
Cr_2O_3	None	....	....	....	....	....
$(CeY)_2O_3$	0.06	....	....	....	....	....
MnO	0.16	0.10	0.20	....	....	....
BaO	0.09	....	0.61	....	....	....
Sum	100.16	99.96	100.48	99.16	....	100.43

I. Nephelite syenite, Beemerville, N.J. M. Aurousseau, anal.
II. Nephelite syenite, Beemerville, N.J. L. G. Eakins, anal. *U.S. Geol. Surv. Bull. 150* (1898), p. 211.
III. Foyaite, Magnet Cove, Ark. H. S. Washington, anal. *Jour. Geol.*, IX (1901), p. 611.
IV. Lujavrite, Rabots Spitze, Kola. V. Hackmann, anal. *Fennia*, XI (1894), p. 132.
V. Norm of I. Symbols, (I) II. 7. 1'. 3. Janeirose.

comagmatic region of the eastern United States, in these respects it differs remarkably from the well-known nephelite syenites of Massachusetts, Connecticut, New Hampshire, and Maine, and also from the nearest similar exposure, that is, from the nephelite syenite of Brookville. The last-named rock resembles the nephelite syenites of New England and shows the essential differences between them and the Beemerville rock (see Table III). The other nephelite syenites of the northeastern United States, and, in

general, those of eastern Canada, are characteristically dosodic, contain less titanium, and where it has been determined, less zirconium than that of Beemerville: they are also more silicic, and some of the Canadian rocks have a marked tendency to show an excess of alumina. The material analyzed by Eakins is termed "the average rock" by Iddings. That used for the analysis here presented was

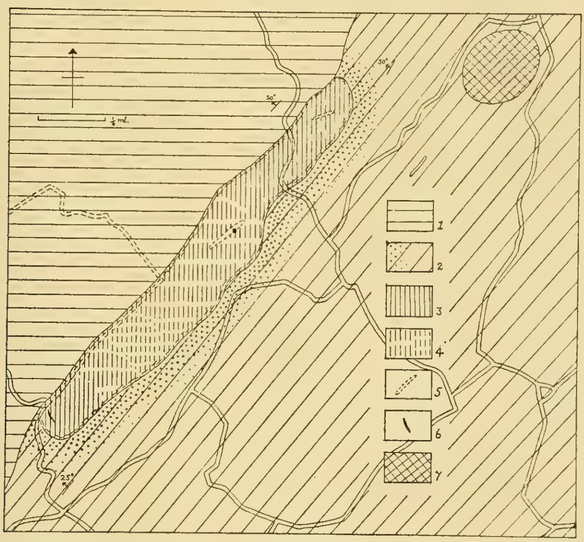

FIG. 1.—The *character* of the Beemerville intrusion, as inferred from the distribution of rock types: (1) Shawangunk conglomerate. (2) Martinsburg shale and contact aureole. (3) Normal nephelite syenite, with occasional nepheline-rich, and lujavritic (marginal) facies. (4) Transition of normal nephelite syenite into darker variety with biotite and titanite. (5) Nephelite porphyry, with tinguaitic and sussexitic facies. (6) Leucite tinguaite. (7) Ouachitite breccia of Rutan's Hill. Diagram partly idealized. Main boundaries from the Franklin Furnace folio. The probable occurrence of a dyke of nephelite porphyry in the northern part of the main mass is suggested by an observation of Emerson, *Amer. Jour. Sci.*, XXIII (1882), p. 308.

collected by Dr. Wolff and is representative of the northern third and the southern extremity of the mass. The non-determination of TiO_2 and P_2O_5 by Eakins of course affects the figures for Al_2O_3.

As has been stated already, the Beemerville nephelite syenite resembles most closely the foyaite of Magnet Cove, Arkansas. An analysis of the latter rock is given in Table I for comparison together with a lujavrite from Umptek, described by Hackmann. The Arkansas rocks are characteristically sodi-potassic, like those

of the Beemerville, though slightly more silicic. The most noteworthy differences are in the titanium and zirconium, and in the ferrous-ferric relationships. The Arkansas syenite apparently contains less of the acmite and more of the diopside molecule than that of Beemerville, and is distinctly poorer in titanium and zirconium. The minor differences among the volatile constituents also are not without interest.

THE NEPHELITE PORPHYRY

The nephelite porphyry, referred to in Kemp's description of the variations of the main mass, is not exposed in a way which permits of a determination of its relationships. It is found in the neighborhood of Mr. T. Conroy's house, near the middle of the main mass, and specimens have been collected from the north of the house, and from the peach orchard southwest of the house. Again quoting from Kemp:

> At the middle of point 4 C on the map the character of the dike changes, as is indicated by the float fragments, for no actual exposures occur. Porphyritic facies appear, and an excellent elaeolite porphyry was found. . . . . Another porphyritic rock occurs along this portion of the dike, which lacks the large phenocrysts of elaeolite. It has, however, others of feldspar, and in the slide shows the same tinguaitic base with a much more prismatic development of the elaeolite in the groundmass.[1]

A small dyke of the same rock occurs two miles northwest of the town of Sussex, and is shown on the map of the Franklin Furnace folio. The nephelite porphyry of the main mass of Beemerville does not reveal its contacts. We believe it to be a dyke of some size, intruding the main mass, and both coarse- (definitely porphyritic) and fine-grained modifications, the latter suggestive of marginal relationship, may be collected north of Mr. Conroy's house.

The rock is typically porphyritic with nephelite crystals, and occasionally with orthoclase. In one specimen small phenocrysts of blue fluorite are quite visible to the naked eye. The groundmass, which has the typical, dull-green color of the tinguaites, is variable in texture in different specimens, and in the finer-grained variety consists of a mosaic of interlocking grains of orthoclase and nephelite, penetrated by minute aegirites. In the more normal variety the aegirites exist in two generations, those of the groundmass forming

[1] J. F. Kemp, *Trans. N.Y. Acad. Sci.*, XI (1892), pp. 66–67.

minute tufts. Orthoclase also shows its twinned development here. The larger aegirites are associated with small but numerous crystals of titanite and a little biotite. A few patches of ilmenite are noticeable, and under high power a little perovskite and apatite may be seen. Cancrinite and hauynite are quite minor constituents, and there is very little development of carbonates. The general mineralogical development is quite similar, except as regards texture, to that of the nephelite syenite itself. Though orthoclase exists in minor amount in some cases, ordinarily it is an important constituent.

TABLE II

	I	II	III	IV	V	VI	VII	VIII	
SiO_2	50.08	49.84	49.96	55.31	45.64	50.16	46.48	Z	0.32
Al_2O_3	17.64	19.47	19.23	21.74	19.50	19.75	19.00	Or	41.14
Fe_2O_3	4.70	4.40	4.55	1.77	3.47	4.28	4.74	Ab	4.19
FeO	2.27	2.24	2.26	1.02	3.34	3.62	2.30	Ne	30.10
MgO	1.12	1.34	1.23	0.47	3.04	1.12	2.49	Hl	0.12
CaO	3.96	4.35	4.15	1.57	4.45	3.10	4.35	Th	0.71
Na_2O	8.10	8.07	8.08	8.77	11.57	7.63	8.46	Nc	0.32
K_2O	7.30	6.71	7.01	6.49	6.96	6.73	6.78	Ac	3.70
H_2O+	....	0.38	0.38	1.94	0.16	3.96	3.31	Di	6.70
H_2O-	0.06	....	0.06						
CO_2	....	0.12	0.12	0.11	....	....	0.36	Wo	3.71
TiO_2	1.75	1.27	1.51	0.07	2.44	....	1.22	Mt	3.48
ZrO_2	....	0.16	0.16	....	....	....	....	Il	2.89
P_2O_5	0.54	....	0.54	Tr.	....	0.13	0.15	Hm	0.80
SO_3	0.39	....	0.39	....	....	....	0.19	Ap	1.34
Cl	....	0.04	0.04	0.60	....	....	0.08	Water	0.44
F	....	....	p.n.d.	....	....	....	....	....	....
Cr_2O_3	....	None	None	....	....	....	....	....	....
$(CeY)_2O_3$	....	0.05	0.05	....	....	....	....	....	....
MnO	0.17	....	0.17	....	0.19	....	Tr.	....	....
BaO	0.32	....	0.32	....	....	....	....	....	....
Sum	....	....	100.21	99.86	100.76	100.48	99.91	....	99.96
Less O	....	....	0.01	0.13	....	....	0.02	....	....
Sum	....	....	100.20	99.73	100.76	100.48	99.89	....	....

I. Nephelite porphyry, Beemerville, N.J. H. S. Washington, anal. Incomplete.
II. Nephelite porphyry, Beemerville, N.J. M. Aurousseau, anal. Incomplete.
III. Average(excluding Al_2O_3 of I) of I and II.
IV. Tinguaite, Monte Mulatto, Predazzo, Tyrol. M. Dittrich, anal. J. Romberg, *Sitzb. Preuss. Akad. Wiss.*, I (1902), p. 748.
V. Nephelite porphyry, Wudjavrtschorr, Upmtek, Kola. V. Hackmann, anal. V. Hackmann, *Fennia*, XI (1894), p. 151.
VI. Tinguaite, Hooper's Inlet, Dunedin, New Zealand. P. Marshall, anal. P. Marshall, *Quar. Jour. Geol. Soc.*, XLII (1906), p. 396.
VII. Leucitite, Etinde Volcano, Kamerun. M. Dittrich, anal. *Sitzb. Preuss. Akad. Wiss.* (1901), p. 299.
VIII. Norm of III. Symbols, II. (6) 7. 1. 3. Janeirose.

Chemically the rock is a foyaite and differs in no essential manner from the nephelite syenite. Indeed, the similarity of the analyses of the nephelite syenite and of the nephelite porphyry is remarkably striking. The latter contains less alumina and titanium than the former, but is a very close parallel to it otherwise. What has been said, therefore, of the affinities of the nephelite syenite applies likewise to the nephelite porphyry. The specimen analyzed was selected with care, and comes from the neighborhood of the peach orchard mentioned. It is, as nearly as possible, the average porphyry.

The rock was analyzed independently by each of us. As the summation from Washington's figures was low, and inspection showed that the figures for alumina were probably at fault, the average of the two analyses was taken, excluding the alumina from I, and correcting that of II only by the deduction from it of one-half of the difference between the two determinations of TiO_2. Column III represents the accepted values. On comparing the rock with others of a similar nature, it is seen that it resembles the nephelite porphyries of other localities. In particular may be mentioned the nephelite porphyry of Julianehaab[1] (Fox Bay type), which is very different mineralogically, however, and the nephelite syenite porphyry of the Val dei Coccoletti, in the Tyrol.[2] The last-named rock is practically the chemical equivalent of the tinguaite of Monte Mulatto, Predazzo, and indeed, so great is the chemical resemblance of the Beemerville nephelite porphyry to certain tinguaitic and leucitic rocks, that we quote the tinguaite of Monte Mulatto (IV of Table II) in preference to the nephelite porphyry. Column V is the nephelite porphyry of Umptek, a more sodic rock, but otherwise similar; while VI and VII are respectively the tinguaite of Hooper's Inlet, Dunedin, New Zealand, and a leucitite from Kamerun. The similarity in chemical composition between the Beemerville magma and the magma which has produced the richly leucitic leucite phonolite of Poggio Muratella, Lake Bracciano, has already been pointed out elsewhere.[3] We desire to stress the simi-

[1] N. V. Ussing, *Geol. Julianehaab, Meddel. om Grönld.*, XXXVIII (1911), p. 275.

[2] J. Romberg, *Sitzb., Preuss. Akad. Wiss.*, I (1911), p. 748.

[3] H. S. Washington, *The Roman Comagmatic Region* (1906), p. 47.

larity of the nephelite porphyry of Beemerville to other nephelite porphyries and similar rocks, because the Beemerville rock, on the basis of a poor analysis, was made the type of the species sussexite. This matter will be discussed below.

CRYSTALLIZATION VARIANTS OF THE BEEMERVILLE MAGMA

The nephelite porphyry and the leucite tinguaite described by Wolff occur within the main mass of nephelite syenite. We believe the first to be a dyke of some magnitude, while the second is a dyke only fifteen inches wide. The leucite tinguaite, also, differs from the nephelite syenite in no other way than in the reversal of the ferrous-ferric relation and a change in the rôle of sulphur (see II of Table III below). The main mass crystallized completely as orthoclase, nephelite, and aegirite. The smaller mass (dyke?) of nephelite porphyry is only a textural variant of the same magma, while the smallest dyke, of the same chemical composition, is a mineralogical variant, having produced a certain amount of leucite and little or no primary orthoclase. The symbols of the three rocks indicate clearly that there has been no chemical differentiation. They are as follows:

$$\left.\begin{array}{l}\text{Nephelite syenite, Beemerville, (I) II.7.1}'\text{.3.}\\ \text{Nephelite porphyry, Beemerville, II.(6)7.1.3.}\\ \text{Leucite tinguaite, Beemerville, II.7(8).1.3.}\end{array}\right\}\text{Janeirose}$$

They all fall in the same subrang. It may be mentioned here that the subrang Beemerose was established from Eakin's analysis, which does not seem to be so representative of the mass as the new analysis here presented. The crystallization variants appear to be due to differences in the rates of cooling of the three rocks, an assumption based upon the respective volumes of the masses concerned. That a nephelite syenite magma is capable of producing leucitic rock is a matter of great interest, and the presence of nearly 12 per cent of leucite in the norm of the Beemerville nephelite syenite may be significant in this respect. The great similarity of the Beemerville magma to certain tinguaites, as already mentioned, is a matter of like nature, that is, the expression of magmas of similar composition in feldspathic and feldspathoid form. In view of some results obtained by Morey and Bowen, on the thermal

relations of leucite and orthoclase,[1] there is no difficulty in accepting the leucite tinguaite of Beemerville as the rapidly cooled equivalent of the nephelite syenite. This interpretation also tends to confirm Kemp's diagnosis of leucite in the true differentiates of the magma, the dykes at Rudeville and Hamburg.

THE OCCURRENCE OF ZIRCONIA AND RARE EARTHS

In the Beemerville rocks the amount of zirconia is rather high. This illustrates the fact that the region east of the Appalachians, from Essex County Massachusetts, through New Jersey as far as North Carolina, and possibly beyond, is a region rich in zirconia. Numerous localities for zircon have been discovered in New Jersey (personal communication from Dr. J. E. Wolff), and its distribution, and that of the rare earths in places, is so well known in Virginia and North Carolina as to need no great comment here. The zirconia is not necessarily confined to sodic rocks, and indeed most frequently occurs in zircon pegmatites, like the well-known pegmatite at Tuxedo, near Hendersonville, North Carolina. The rare earths occur mostly in allanite, which has a fairly wide distribution in Maryland and Virginia. Our determination of the rare earths in the nephelite syenite and nephelite porphyry is the first record of them in northern New Jersey. A number of unpublished analyses of aegirites, by Washington, indicate that the rare earths of the Beemerville rocks occur in the aegirite. The bulk of the rare earth precipitates in our analyses was too small to admit of any separation being made, but the chemical behavior during the determinations suggests that yttrium preponderates over cerium, and that thorium is present.

As the literature of the alkalic rocks of northern New Jersey is scattered, and in part somewhat old, we append the superior analyses of other rocks of the district, with which we have not dealt directly here. We have included an inferior analysis of the ouachitite of Rutan's Hill, by Kemp, as there is no other chemical information extant concerning the basic lamprophyres. The summation of this analysis is low, in spite of the fact that the iron is all expressed as Fe_2O_3, and the water and CO_2 are merely repre-

[1] G. W. Morey and N. L. Bowen, *Amer. Jour. Sci.*, IV (1922), p. 1.

sented as "loss on ignition." As regards the other analyses of the table, the MnO of II is probably too high, and the non-determination of P_2O_5 and TiO_2 in III of course render the figures for alumina too high. All other analyses of the alkalic igneous rocks from this region we have discarded as unfit for use.

TABLE III

	I	II	III	IV
SiO_2	54.68	50.00	40.71	40.47
Al_2O_3	21.63	20.03	19.46	11.86
Fe_2O_3	2.22	0.98	7.46	17.44
FeO	2.00	3.98	6.83	
MgO	1.25	0.69	6.21	3.10
CaO	2.86	3.41	11.83	16.80
Na_2O	7.03	8.28	1.80	1.90
K_2O	4.58	8.44	3.26	4.21
H_2O+	1.88	1.50	1.53	3.60
H_2O-	0.27	0.10		
CO_2	None	0.22	0.74	....
TiO_2	0.79	0.99	....	....
P_2O_5	0.28	0.21	....	....
SO_3	0.07	....	....	....
Cl	None	Tr.	....	....
F	0.22	n.d.	....	....
FeS_2	....	0.54	....	....
MnO	Tr.	0.50	0.18	....
BaO	0.05	None	....	....
Sum	99.81	99.87	100.01	99.38
Less O	0.09	....	....	....
Sum	99.72	99.87	100.01	99.38

I. Nephelite syenite, Brookville, Hunterdon Co., N.J. G. Steiger, anal. *Amer. Jour. Sci.*, VIII (1899), p. 423.

II. Leucite tinguaite, Beemerville, N.J. J. E. Wolff, anal. *Bull. Mus. Comp. Zoöl. Harvard*, XXXVIII (1902), p. 276.

III. Minette, Franklin Furnace, N.J. L. G. Eakins, anal. *U.S. Geol. Surv. Bull. 150* (1898), p. 238.

IV. Ouachitite, Rutan's Hill, Beemerville, N.J. J. F. Kemp, anal. *Amer. Jour. Sci.*, XXXVIII (1889), p. 133.

THE STATUS OF SUSSEXITE

Brögger, in working out the grorudite-tinguaite suite of the Kristianiagebiet, extrapolated from his analyses of the series, and calculated an end member for the suite, the composition of which is shown in column II of Table IV. No rock corresponding to this hypothetical composition was found in the Kristianiagebiet,

but Brögger considered that Kemp's analysis of the Beemerville nephelite porphyry, together with the description, indicated that a rock of the hypothetical, calculated composition, and corresponding to an end member of this series, actually existed. He therefore defined the species now known as *sussexite*,[1] making the Beemerville rock the type, in the following terms:

Gesteine wie diejenigen von Beemerville waren aber früher nur wenige bekannt, jedenfalls nur wenige analysirt; sie bilden einen ganz distincten chemischen Typus, wie sie auch geognostisch durch ihre häufige Verknüpfung mit Nephelinsyeniten charakterisirt sind; dementsprechend sind sie reich an Alkalien, arm an Kalk und Magnesia und mässig reich an Eisenoxyden, aber mit sehr hohem Al_2O_3 Gehalt. Es wäre entschieden irreleitend, diese Gesteine als Nephelinite zu bezeichnen, nur deshalb weil sie aus Nephelin (und Aegirin) bestehen.

A sussexite, according to Brögger's definition, is a nephelite porphyry either poor or lacking in orthoclase, and therefore a persodic or dosodic rock, resembling the urtites and ijolites in composition.

TABLE IV

	I	II	III
SiO_2	45.18	45.0	47.43
Al_2O_3	23.31	25.0	23.60
Fe_2O_3	6.11	6.5	4.59
FeO			1.20
MgO	1.45	1.5	1.20
CaO	4.62	2.0	0.67
Na_2O	11.16	12.0	15.08
K_2O	5.95	7.0	2.00
H_2O	1.14	1.0	....
TiO_2	....	....	0.10
Sum	98.92	100.0	99.09

I. Nephelinitic facies of nephelite porphyry, Beemerville, N.J. J. F. Kemp, anal. (?) J. F. Kemp, *Trans. N.Y. Acad. Sci.*, XI (1892), p. 67. Brögger's type for the species Sussexite.

II. Hypothetical Sussexite, calculated by extrapolation from the Grorudite-Tinguaite series. W. C. Brögger, *Eruptivgest. des Kristianiagebietes*, I (1894), p. 172.

III. Sussexite, Penikkavaara, Kuusamo, Finland. M. Dittrich, anal. V. Hackmann, *Bull. Comm. Géol. Finlande*, XI (1900), p. 22.

Kemp's analysis (see I of Table IV) indicates that the sample he analyzed corresponded fairly closely to Brögger's definition of

[1] W. C. Brögger, *Eruptivgest. des Kristianiageb.*, I (1894), p. 173.

the type. It is certainly dosodic. We have shown here that the nephelite porphyry of Beemerville is a sodipotassic rock, in no important respect different from other nephelite porphyries, and we can only conclude that the sample chosen for analysis by Kemp was not representative. Kemp's own descriptions of the nephelite porphyry show that the rock he described was not abnormally poor in orthoclase. Consequently the Beemerville rock cannot maintain its position as the type sussexite. Only one rock corresponding to Brögger's original definition has been analyzed so far, it being the sussexite of Kuusamo, Finland, described by Hackmann (see III of Table IV). As it establishes the existence of the species (the existence of which may be said to have been predicted by Brögger), the name sussexite should remain in use, in the sense of Brögger's definition. Sussexite is essentially a nephelite porphyry devoid of feldspar, or, in other words, a porphyritic urtite.

Rocks of the nephelite syenite family tend to lack homogeneity within the mass, and too much care cannot be exercised in the selection of material for analysis, which will correspond well with the material upon which the petrographic descriptions are based. Another instance showing lack of correspondence between the chemical analysis and the mineralogical description is the mariupolite described by Morozewicz.[1] The analysis of this rock does not permit of the existence of the amount of nephelite it is said to contain (according to the description).

The Beemerville nephelite porphyry has been widely accepted as the type of sussexite. Iddings calculated the ratio

$$\frac{Na_2O+K_2O}{SiO_2}$$

for Brögger's grorudite-tinguaite series and found that the Beemerville rock, from Kemp's figures, lay upon a prolongation of the approximately straight line representing the series in the diagram.[2] The Beemerville rock, however, is not a differentiate at all, but, as we have shown, a textural variant of the main mass of the nephelite syenite.

[1] J. Morozewicz, *TMPM*, XXI (1902), p. 230.

[2] J. P. Iddings, *Jour. Geol.*, III (1895), p. 357.

SUMMARY

The scattered contributions to the geology and petrology of the alkalic igneous rocks of northern New Jersey are reviewed in chronological order, and a general account of these rocks is given.

The large mass of nephelite syenite northwest of Beemerville is described and is interpreted as a lenticular sill or a flat laccolith of foyaite, intruded by a mass of nephelite porphyry (probably a dyke) and by a small dyke of leucite tinguaite.

New analyses of the nephelite syenite (foyaite) and of the nephelite porphyry are presented, and the affinities of these rocks and of the leucite tinguaite are discussed. It is concluded that these three rocks are textural and mineral variants, without chemical differentiation, of the same magma.

It is shown that the nephelite porphyry is not a sussexite, as formerly supposed, and the status of sussexite as a rock variety is considered, with the conclusion that the name should be retained in its original sense, but that the nephelite porphyry of Beemerville can no longer be regarded as the type of the variety.

The presence of zirconium and the rare earths in the Beemerville rocks has been demonstrated, and the wide distribution of these elements in the region east of the Appalachians is briefly discussed.

WASHINGTON, D.C.
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INTRAFORMATIONAL CORRUGATED ROCKS

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CONTENTS

INTRODUCTION

It is the purpose of this paper to enter into a general discussion of intraformational contorted rocks, with emphasis upon the modes of origin of the different types. During the last eighty years various examples have been described, but it is surprising how few are the cases which have been discussed in sufficient detail to furnish the data necessary for their classification on the basis of origin. Evidently these interesting and often puzzling structures have not received the attention which they deserve. In the present attempt to make a tentative genetic classification of intraformational corrugations, examples, mainly from American localities, are given to illustrate the various types. Because of the lack of certain critical data, it is difficult or impossible to be very sure of the proper classification of some of the cases.

DIFFERENTIAL MOVEMENT ACCOMPANYING THRUST FAULTING

Excellent examples of corrugated strata between practically undisturbed strata occur in the walls of the postglacial gorge at

Trenton Falls, New York, where the contorted beds lie at two distinct horizons within the Trenton limestone formation, there about 300 feet thick. The lower contorted zone, 4 to 6 feet thick, is visible only near the crest of the lower part of High Fall and in the upper end of the gorge near Prospect Village where the strata are highly inclined against a thrust fault surface. The upper contorted zone, 5 to 15 feet thick, is well exhibited along the path opposite High Fall (Fig. 1, upper part) from which place it is clearly traceable in the walls of the gorge for nearly 2 miles northward to Prospect (Fig. 1, lower part).

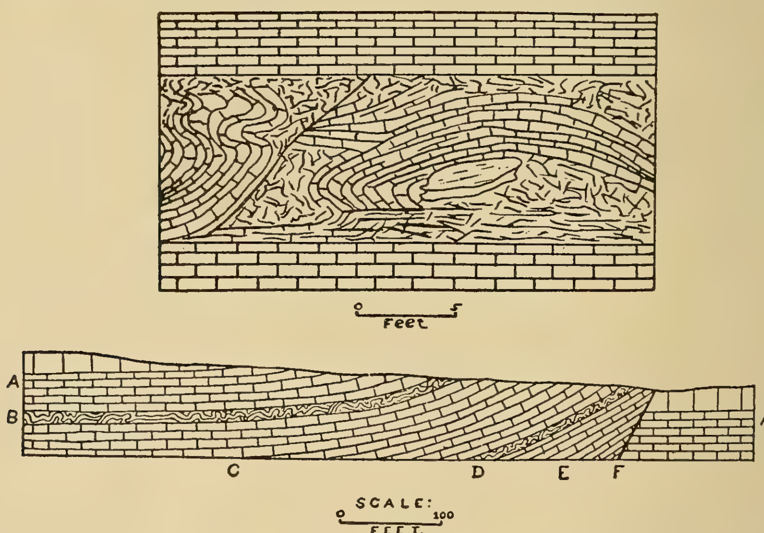

FIG. 1.—Upper figure: sketch of part of the upper contorted zone at Trenton Falls, New York. Lower figure: north-south structure section showing the positions of the contorted zones within the Trenton formation and their relation to the thrust fault at Trenton Falls, New York.

In both the undisturbed and the corrugated portions of the formation the impure limestone layers average only a few inches in thickness, and they are separated by thin partings of shale. Within the contorted zones the strata are in some cases scarcely disturbed; in some cases they are only gently folded or tilted; but most commonly by far they are highly folded, contorted, and even fractured.

The explanation offered by the writer is that the contorted zones were produced by differential movements within the mass of the Trenton limestone. The displacement (140 feet) of the thrust fault at Prospect Village was sufficient to cause the beds of the middle Trenton to be shoved over the upper Trenton. Figure 1 (lower part) shows the relation of the contorted zones to this fault. It is easy to see how, when the force of compression was brought to bear in this region, the higher Trenton beds on the upthrow side must have moved more easily and consequently faster than the lower Trenton beds. For instance, the portion *A* in Figure 1 (lower part) being separated from *C* by an intermediate mass *B* of possibly slightly less rigidity moved over *C* and caused the portion *B* to become ruffled or folded and fractured because this portion took up most of the differential movement. The portion *B* needed to be only slightly less rigid than the adjacent strata and this slightly reduced competency is due to somewhat thinner limestone layers separated by relatively thicker shale partings. A similar explanation applies to the lower contorted zone. According to this explanation the corrugated zones indicate horizons along which the differential movements took place, and no great amounts of differential movement were necessary to produce the contortions.

Grabau[1] states that

> These disturbances at Trenton Falls have been variously explained, the general conclusions of geologists being either: (1) that they were truly tectonic —lateral pressure having resulted in the folding of certain strata while others took up the thrust without deformation, or (2) that they were due to squeezing out of certain layers under the weight of overlying rock masses. Both explanations are unsupported by the detailed characteristics of the folds and their relationship to the enclosing layers.

The writer agrees that these two explanations must be ruled out, but he does not agree with Grabau who accepts Hahn's[2] subaqueous slumping or gliding hypothesis, described later in this paper, without even mentioning the tectonic differential slipping hypothesis (above outlined) which was first applied by the writer[3] to the Trenton

[1] A. W. Grabau, *Principles of Stratigraphy* (1913), p. 784.

[2] F. Hahn, *Neues Jahrb. Beil.*, Vol. XXXVI (1913), pp. 1–40.

[3] W. J. Miller, *Jour. Geol.*, Vol. XVI (1908), pp. 428–33.

Falls contorted zones in 1908, and further elaborated in 1915.[1] Arguments against Hahn's hypothesis are there entered into somewhat in detail. In the opinion of the writer, differential movement (not always as an accompaniment of thrust faulting) is involved in many, if not most, cases, of intraformational corrugations.

Intraformational contorted beds of essentially the same origin as those at Trenton Falls, only on a larger scale, occur within the straight-bedded limestones of Turtle Mountain, Frank, Alberta,

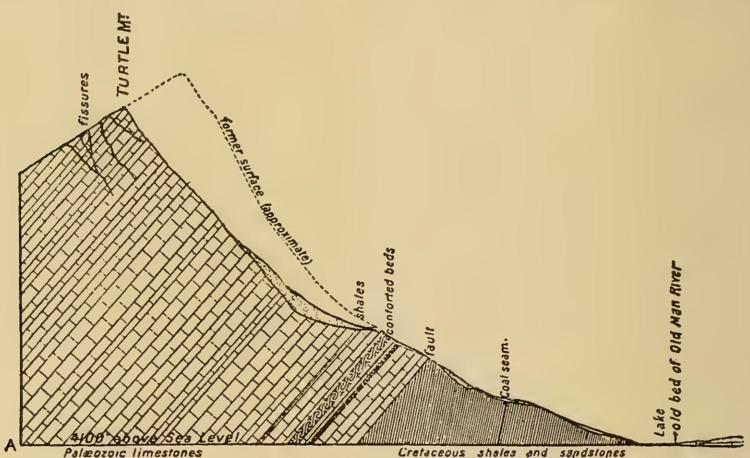

FIG. 2.—Section showing the position of the contorted limestones and the relation of the contorted beds to the great thrust fault at Frank, Alberta, Canada. (After R. W. Brock.)

Canada. Accompanying Figure 2 after Brock[2] shows the position of two corrugated zones of more shaly material intercalated between straight beds of limestone and parallel to a great thrust fault on its upthrow side. The writer would explain these corrugations as due to differential slippings within the limestone with resultant crumpling of the more shaly layers during the process of thrust faulting of the Paleozoic limestone over the Cretaceous strata.

Many years ago Logan,[3] in his description of a section 1,210 feet in thickness of Devonian strata on the Forillon peninsula of

[1] W. J. Miller, *N.Y. State Mus. Bull. 177* (1915), pp. 135–43.

[2] R. W. Brock, *Dept. Interior Canada, Ann. Rept.*, Part 8.

[3] W. Logan, *Geol. Can.* (1863), p. 391.

Gaspé in the Gulf of St. Lawrence, called attention to a remarkable example of intraformational corrugations. Logan says:

It would appear as if the layers, after their deposit, had been contorted by lateral pressure, the underlying stratum remaining undisturbed, and had then been worn smooth before the deposition of the next bed. Where the inverted arches of the flexures occur, some of the lower layers are occasionally wanting as if the corrugated bed had been worn on the under as well as the upper side. The corrugations are precisely in the direction of the dip, and the peculiarity is not confined to a small part of the deposit.

He states that the same structure occurs at localities a mile apart.

FIG. 3.—Contorted strata within Devonian limestone at Cape Gaspé, Quebec. (After J. M. Clarke.)

John M. Clarke, who has observed the Gaspé occurrence, and who has kindly permitted the use of the accompanying picture (Fig. 3), says:

Crinkled strata lying between strata which show no evidence of dislocation are not of infrequent observation but, in most of the recorded instances, the crinkled layer is of softer stuff (that is, a highly aluminous mud rock) than the rigid beds above and below. The brilliant exhibition of this phenomenon on the cliffs of Cape Gaspé, first sketched by Sir William Logan, is not of this character. Here the middle deformed beds are of thin limestone leaves like those which bound them. They are crumpled into sharp, much involved and overlapping curves in which the limestone plates are broken sharply across. It seems very doubtful if any other explanation can be brought forward for

this exceptional occurrence than that generally adopted for those of the first named category; a sliding of soft sea bottom deposits on a sloping surface under gravity, helped forward perhaps, if on a large scale, by earthquake shock or some other jolt-like impulse. . . . . It follows from the conception of these structures that the deformation was contemporaneous, and preceded the deposition of the overlying beds.[1]

For the reasons below listed the writer is strongly inclined to the conclusion that the corrugated zone at Gaspé developed as a result of differential movement within a great block of strata while it was being thrust faulted. (1) If we accept the hypothesis of subaqueous sliding, it is necessary to attribute the nearly straight upper surface truncating the contorted zone to erosion, but the very character and uniformity of both the contorted and inclosing strata seem to render this extremely improbable; (2) the worn character of both the upper and lower surfaces of the contorted zone, with certain beds locally missing as noted by Logan, are best explained on the basis of differential movement within the mass of limestone; (3) that the conditions were very favorable for differential movement is borne out by the fact that the contorted zone lies not far from the bottom of a large block of Devonian strata which has been extensively thrust faulted over Cambro-Ordovician strata; (4) the strike of the contorted zone is approximately parallel to the strike of the thrust fault; (5) the corrugations conform to the direction of dip of the inclosing beds; (6) according to Logan's section, the corrugations developed just where the conditions were most favorable for differential movement, that is, in the weakest (most shaly) part of a mass of the strata 200 feet thick with appreciably more arenaceous and resistant strata above and below this mass; and (7) the rather puzzling occurrence of the two nearly straight, thin beds within the contorted zone (see Fig. 3) may be more reasonably explained on the basis of differential movement than on the basis of subaqueous gliding because, as revealed by careful examination of the figure, these layers, as well as the layers capping the contorted zone, show clear evidence of having been deformed and even cut across locally by the corrugations, thus indicating that the contortions took place after deposition of those layers.

[1] Personal communication from Dr. Clarke.

DIFFERENTIAL MOVEMENT ACCOMPANYING NORMAL FAULTING

Up-drag of strata commonly takes place as a result of friction during movement on the downthrow sides of normal faults. Under proper conditions drag folds of the nature of intraformational corrugations develop as a result of differential movement of the bending strata. A good example has been observed by the writer in the bed of the Connecticut River just below the dam at Holyoke. A normal fault is clearly traceable in the bed rock across the river a few rods below the dam. From the fault south for 150 yards the strata (sandstone and shale) show dips of 25 to 40 degrees to the south due to up-drag, and they strike parallel to the fault. About 150 yards south of the fault there is a notably disturbed zone of thin-bedded dark shale with strike parallel to that of the fault. It shows clearly along the strike for 200 yards. The disturbed zone, varying in thickness between 4 and 10 feet, is overlain by fairly well-bedded red sandstone, and underlain by thin-bedded dark shale much like that of the disturbed zone. Next below there is sandstone. The folded zone does not terminate abruptly at either summit or base, but the top is much the more regular, coming close to the overlying sandstone. Even the sandstone, for a foot or so above the shale contact, is locally somewhat bent. The whole body of the rock in the bed of the river south of the fault plainly shows the effects of differential movements which took place during the process of normal faulting. One belt of weak, thin-bedded shale overlain by relatively rigid sandstone became moderately corrugated, the corrugations being of the nature of drag folds produced by differential movements. That the corrugations must have developed after the deposition of the overlying sandstone layers is proved by the fact that the lower part of the sandstone is in many cases moderately bent just like the immediately underlying shale. It seems impossible to escape the conclusion that this corrugated zone is of tectonic origin, that is, the result of differential movement accompanying normal faulting.

DIFFERENTIAL MOVEMENT ACCOMPANYING REGIONAL FOLDING

The principle of differential movement of strata is well illustrated in many regions of notably folded rocks. Differential move-

ments take place between the relatively more competent beds with not uncommon development of corrugations of the nature of drag folds between them. According to Leith: "The stronger beds tend to assume the 'parallel' type of folds in which the principal adjustment is between the beds rather than within them. This readjustment or slipping is concentrated in the intervening weaker layers. The folds of the weaker layers are really 'drag folds' due to differential movement between the controlling harder layers."[1]

Excellent examples of intraformational corrugated strata believed to have resulted from differential movement accompanying regional folding were observed by the writer some years ago at Baldhead Cliff near Ogunquit, Maine. The perfectly stratified thin-bedded rocks are there interbedded quartzite and phyllite. That the region has been subjected to severe lateral compression is evidenced by the fact that the strata stand in nearly vertical position. Figure 4 is a ground plan sketch showing the detailed structure of one of these corrugated zones about 9 feet thick, although the quartzite layers are really less conspicuous than indicated in the diagram. The corrugated zone, consisting very largely of phyllite, is not sharply delimited from the adjacent straight layers of predominant quartzite on either side. In most cases slight faulting has taken place along the axes of the sharp folds, but, as a rule, individual sharp folds or faults rarely extend all the way across the contorted zone. The folds are uniformly overturned toward the east. Fracture cleavage is well exhibited in the phyllite layers a few inches thick which lie within the quartzite on either side of the contorted zone. The cleavage cracks are uniformly inclined toward the east, as are the folds. "When a slate or shale is folded between two competent layers, such as quartzite, the cleavage produced in the slate affords clear evidence of slipping or shearing between the quartzite beds."[2]

All the evidence points to the tectonic genesis of the above-described intraformational corrugated strata. The corrugations must have developed after all the strata were deposited because the folded zone grades into the non-folded strata on either side.

[1] C. K. Leith, *Structural Geology* (1913), p. 114.

[2] *Ibid.*, p. 119.

Under conditions of differential movement the wide belt of predominant phyllite yielded by development of corrugations, while the thin bands of phyllite between much quartzite on either side yielded by development of fracture cleavage.

In the Marquette synclinorium of Michigan intraformational corrugations are shown on large scales in the slate formations which lie between quartzite formations.

During the summer of 1921 the writer was impressed by the fine exhibitions of intraformational contorted strata of Proterozoic

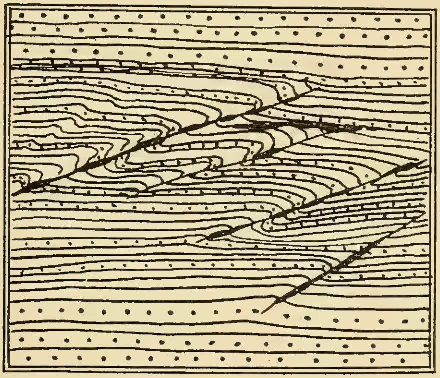

FIG. 4.—Ground-plan sketch of intraformational corrugated phyllite and quartzite near Ogunquit, Maine. The black lenses are quartz. Contorted zone about 9 feet wide.

age on both small and large scales in Glacier National Park. In the wall of the great Swiftcurrent cirque, only a few rods from the trail, the strata are notably folded and even crumpled through a thickness of 30 to 40 feet, and for a distance of a few hundred feet, while on all sides the strata are undisturbed except for the moderate regional tilting. The folding rocks are not sharply separated from the others. On the grand scale the strata are very irregularly contorted through a thickness of hundreds of feet in the face of the mountain between Gunsight Lake and Gunsight Pass with non-contorted strata above, and also at the same general horizon on either side. These contorted beds have quite certainly resulted from local differential movements within the great body of Proterozoic strata either during the development of the synclinal structure

of the park, or during the tremendous process of thrust faulting of the district, or both.

In a discussion of the highly folded gold-bearing series of Nova Scotia, Faribault[1] has figured and described some interesting cases of intraformational corrugated quartz veins in slate lying between beds of quartzite. He says: "Interstratified (quartz) veins often exhibit a remarkable folded or corrugated structure within the beds of slate that contain them. The corrugations, or crenulations, usually occur at or near the apex of the anticline, and run parallel with one another and in a direction approximately parallel with the axis of the fold." He believes (1) that the veins were formed during the folding of the region; (2) that, due to differential motion within the relatively weak or plastic slate containing veins which were formed early in the folding process, the veins and inclosing slate were corrugated; and (3) that such motion resulting in corrugations took place mainly at the apexes of the folds.

DIFFERENTIAL SQUEEZING ACCOMPANYING REGIONAL FOLDING

Lateral pressure may result in the folding of certain weaker strata while adjacent more resistant strata take up the thrust either without so much folding or by being fractured instead of folded. Intercalated beds of limestones are especially likely to yield in this manner. Interesting effects of differential squeezing in the folded Algonkian strata of the Marquette district of Michigan have been described by Van Hise, Bayley, and Smyth[2] who say:

> Along the contacts of the (Kona) dolomite beds and the quartz(ite) layers accommodation was necessary, and in places a bed of limestone may be seen bent into a series of anticlines and synclines, the overlying quartzite not being similarly bent, but being compressed and brecciated, thus making a pseudo-conglomerate. . . . . When the series was folded the more plastic limestone yielded to the pressure, in both a major and a minor way, by folding, while the brittle quartzite was fractured through and through, the movement of the fragments over one another, and of the beds as a whole, being sufficient to truncate the minor waves of the marble.

[1] E. R. Faribault, *Can. Geol. Surv., Guide Book No. 1*, Part 1 (1913), pp. 174–88.

[2] Van Hise, Bayley, and Smyth, *U.S. Geol. Surv., Mon. 28* (1897), pp. 242–43.

Even in this case some shearing action or differential slipping was a factor in the process.

Prouty[1] has described the crumpling of thin beds of marble between thick beds which latter yielded by fracturing and faulting.

The principle of differential squeezing appears to be not uncommon in various regions of folded strata.

DIFFERENTIAL MOVEMENT UNDER THE ACTION OF GRAVITY

Fine examples, believed by the writer to belong in this category of intraformational contorted strata, are to be found in the post-glacial clays of various regions. The following observations made by the writer upon the clays in and near Northampton, Massachusetts, give a fair idea of the nature of the foldings and their origin. In the bank of the Connecticut River 2 miles east of Northampton, 12 to 14 feet of nearly horizontal, thin-bedded, perfectly stratified clays are overlain by 10 to 15 feet of stratified sands. The clay contains two contorted zones—a lower one 1 to 2 feet thick, and an upper one 4 to 8 inches thick—separated by 8 or 9 feet of the ordinary non-contorted clay. These corrugated zones are clearly traceable for several hundred feet. Immediately above each contorted zone, the non-contorted layers are in many places somewhat wavy or slightly folded. Different portions of the same contorted zone show different degrees of folding, the clay beds in some cases being only moderately folded, while in others they are intensely twisted, pulled apart, and even overturned. Some of the straight beds contain notable amounts of very fine sand, but the contorted beds consist of distinctly less sandy clay. The corrugations almost invariably have strikes parallel not only to each other but also to the notable dip (several degrees) of the clay beds in general. The under surface of each contorted zone is usually very straight, while the upper surface is commonly somewhat irregular (Fig. 5).

In the South Street clay pit of Northampton the writer has observed a very fine highly contorted zone of clay sharply intercalated between beds of clay whose stratification surfaces are almost straight. The straight beds consist of alternating, very fine-grained,

[1] W. F. Prouty, *Geol. Surv. Ala., Bull. 18* (1916), p. 170.

sandy clays and pure clays, while sandy clays are distinctly less conspicuous among the contorted beds. Figure 6 represents a detailed sketch of part of this corrugated zone, a feature of exceptional interest being the only slightly disturbed layer of fine-grained, sandy clay lying in the midst of the contortions. This contorted zone about 8 inches in thickness may be traced for a number of rods in the walls of the clay pit, but its full extent is unknown. Above it about a foot there is another corrugated zone lying between prac-

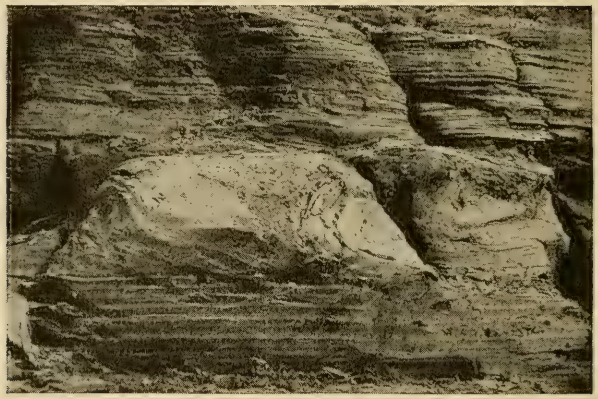

FIG. 5.—Highly contorted zone (8 inches thick) of clay between practically undisturbed beds of clay and sandy clay in the bank of the Connecticut River 2 miles east of Northampton, Massachusetts.

tically undisturbed beds. Within the clay pit the beds show a very appreciable dip of at least several degrees to the southeast.

It seems impossible to explain intraformational contorted clays like those just described except as a result of differential movements after the clays overlying the contortions were deposited. An explanation commonly given for such phenomena, but rarely if ever supported by anything like reasonable proof, is that the contortions were caused either by ice thrust, or the bumping or crowding of icebergs on surface layers which were afterward covered by more clays. Some facts opposed to such a hypothesis are: (1) the remarkably uniform thinness of the corrugated zones of such wide extent which could hardly have resulted from ice action upon surface layers, the development of such zones under considerable

weight of overlying materials being far more plausible; (2) there are no notable irregularities or depressions at the tops of the corrugated zones such as must have developed in the case of crumpling of surface layers with these depressions first filled by the succeeding deposits; (3) the moderate disturbance of the beds immediately overlying the corrugated zones, while those just underneath are distinctly straighter, strongly point to differential movements after the overlying beds were laid down; and (4) the only slightly disturbed thin bed of fine sandy clay in the midst of the contorted South Street clays, as well as the relatively straight beds of similar material just above and below the contortions, are best accounted

Fig. 6.—Contorted zone in South Street clay pit of Northampton, Massachusetts

for on the basis of differential movements, the thin, clay-rich, very plastic beds having yielded by crumpling, while the much less plastic sand-rich beds did not crumple. It is out of the question to look upon the upper surfaces of the corrugated zones as erosion surfaces because these perfectly stratified, thin-bedded, postglacial clays everywhere plainly show that they were deposited without a break in very quiet water.

The hypothesis of differential movement does not necessarily preclude the possibility of subaqueous slumping for it is plausible to think of differential movements within masses of the clays which may have shifted more or less down the gently sloping delta fronts in the postglacial lake of the Connecticut Valley. The action of gravity alone, or of gravity aided by an occasional earthquake, may have caused the movements. It is more likely, however, that

the movements mostly took place much later, that is, since the river has cut deeply into the distinctly dipping clay deposits so that, under the action of gravity or gravity aided by earthquake shocks, overlying beds have moved differentially over lower-level beds in the general direction of the dip. In some local cases differential movements within clays may possibly have been caused by the crowding action of ice against upper portions of clay deposits as explained later under another caption.

A few examples of apparently similar intraformational clays from other regions will be cited, with various explanations which have been offered to account for them. In regard to corrugations in clays near Boonville, New York, Vanuxem[1] eighty years ago said: "These interesting forms of disturbance were no doubt the result of unequal, local, and lateral pressure." A very similar excellent example of intraformational sand and clay in the Devil's Lake region of Wisconsin is figured and described by Salisbury and Atwood,[2] who say: "The grounding of an iceberg on the surface before the overlying layers were deposited, or the action of lake ice, may have been responsible for the singular phenomenon."

M. E. Wilson has described and figured[3] interesting cases of intraformational contorted and broken clays in Timiskaming County, Quebec, and in regard to their origin he says: "Whatever the cause of these peculiar deformational structures, it is evident that they were contemporaneous with deposition, for the stratification is uniform in both the overlying and underlying beds."

In Albany County, New York, according to Nason,

> A layer of blue clay about a foot in thickness and one hundred feet long is crumpled and gnarled, appearing as though its laminae had been disturbed by some dragging or shoving weight, while above and below the layers are exactly parallel and wholly undisturbed. . . . . Bearing in mind the fact that the clay banks are underlain by sand, the water circulating through these sands gradually undermines the clay bank and tilts it to such an angle that one part of a bed would slide over the other, only leaving visible marks along the particular stratum disturbed, and in the form of crumplings. Many of the clays lie at an angle to the horizon, and only a slight tilt would suffice to give rise to a slip.[4]

[1] L. Vanuxem, *Geol. N.Y.*, Part 3 (1842), p. 215.

[2] Salisbury and Atwood, *Jour. Geol.*, Vol. V (1897), p. 143.

[3] M. E. Wilson, *Can. Geol. Surv., Mem. 103* (1918), p. 142 and Pls. 15–16.

[4] F. L. Nason, *N.Y. State Mus. Rept. 47* (1893), p. 465.

It is to be noted that Nason's explanation clearly involves the principle of differential movement which is advocated by the present writer as the cause of most intraformational contorted clay beds.

SUBAQUEOUS GLIDING OR SLUMPING

The hypothesis of subaqueous gliding has been elaborated by Hahn[1] who has considered most cases of intraformational contorted strata to belong in that category. According to Hahn's hypothesis a lenslike mass breaking loose from any cause (e.g., earthquake shock) would glide down a subaqueous slope and, because of the striking of some obstacle on the bottom and increased friction and water pressure, the gliding mass would come to rest only after it had become considerably deformed or contorted. Sediments would then be deposited in normal order on top of the crumpled layer. The most intense folding would be toward the front of the transposed mass, and of course the strike of the folds would be at right angles to the direction of the moving mass. Conditions for such gliding are regarded as favorable at many places on the marginal sea bottom.

In the paper above cited, Hahn especially refers to the intraformational contorted zones at Trenton Falls, New York, as typical examples of submarine slumping among ancient strata. In a paper already published the writer has given reasons for believing that Hahn's hypothesis cannot possibly account for the Trenton Falls occurrences.[2] Hahn has regarded most cases of intercalated corrugated strata as results of subaqueous gliding, while the present writer regards most of them by far as results of differential movements within the masses of strata.

T. C. Brown[3] has described what appears to be a clear case of intraformational folding in Paleozoic strata near Bellefonte, Pennsylvania. In regard to this occurrence Brown says in part: "At periodic intervals these beds of calcareous mud and intermingled pebbles slumped or slid along the bottom under the influence of gravity. At the time of the slump or slide the matrix around the pebbles consisted of incoherent lime mud or paste. As it moved

[1] F. Hahn, *Neues Jahrb. Beil.*, Vol. XXXVI (1915), pp. 1–41.

[2] W. J. Miller, *N.Y. State Mus. Bull. 177* (1915), pp. 140–43.

[3] T. C. Brown, *Jour. Geol.*, Vol. XXI (1913), pp. 241–43.

it developed unsymmetrical waves or ripples in its mass." After the mass came to rest more lime mud was deposited upon its surface. Since then the whole has been solidified. The contorted zone shows notable variations in thickness from a few inches to several feet (Fig. 7). Certain criteria which seem to rather definitely place this occurrence in the category of subaqueous gliding, and which particularly distinguish it from the above-described examples believed to have resulted from differential movements after deposition of the overlying layers, are the following: (1) the notable variations in thickness of the contorted zone locally, even within a few feet; (2) the very irregular upper surface of the folded zone,

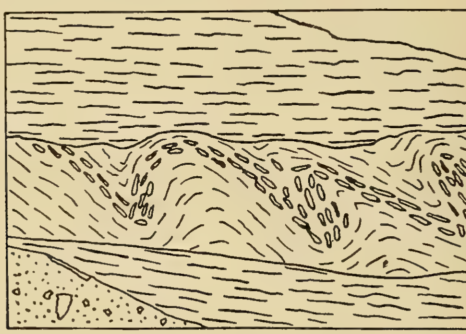

FIG. 7.—Folded limestone and limestone-conglomerate, several feet thick, between non-folded beds near Bellefonte, Pennsylvania. (After T. C. Brown.)

and the rather regular under surface; (3) the bulging of the immediately overlying strata over the little anticlinal folds; and (4) the distinct evidence of the filling of the depressions on the upper surface of the corrugated zone before the general layers of overlying materials were laid down.

D. W. Johnson has kindly allowed me to reproduce a picture (Fig. 8) of a moderately corrugated zone within the cross-bedded Triassic red beds near Kanab, Utah. Regarding the occurrence he says:

> The crumpling and faulting must have taken place during the process of deposition, for the erosion plane beveling the deposit a few inches above the corrugations, and upon which the next layer of cross-bedded sand was deposited, shows no disturbance. I have therefore attributed the corrugations and miniature faults to slumping or settling of the deposit as it was built forward, delta-like, under the influence of current action.[1]

[1] Personal communication from Professor Johnson.

In view of the fact of the very moderate degree of corrugation, a slight amount of subaqueous slumping or forward settling, perhaps under earthquake impetus, would have produced the structures. There may have been no actual gliding over the lower erosion surface at all. Erosion intervals, under the conditions of shifting currents during the deposition of the cross-bedded sandstones, would be expected. The corrugations of the disturbed zone might possibly have resulted from slight differential slipping

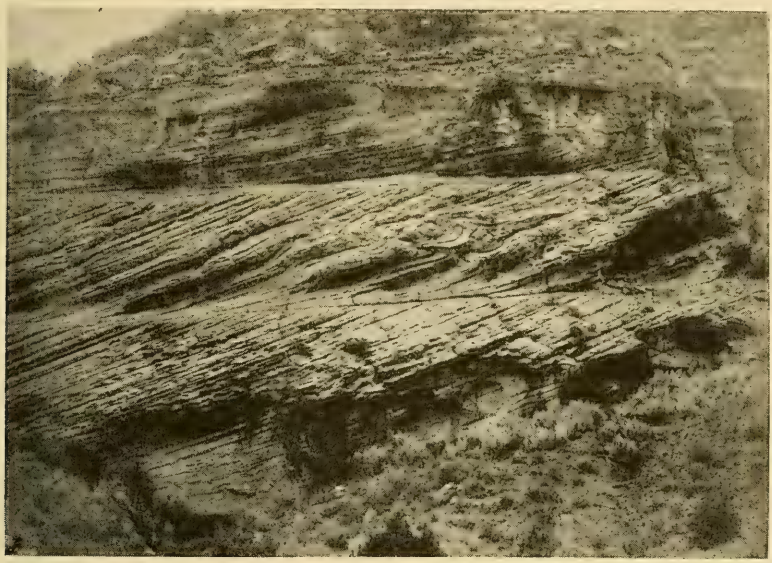

FIG. 8.—Intraformational cross-bedded, corrugated, Triassic sandstone near Kanab, Utah. (After D. W. Johnson.)

along the erosion surfaces but, in spite of certain outward resemblances to the intercalated contorted zones above described as due to differential movement after deposition of the immediatley overlying beds, the writer believes that the structures in the Kanab occurrence are essentially different, and that they are correctly interpreted by Johnson.

Norton[1] has discussed subaqueous gliding as a cause of a certain type of breccias, but examples certainly coming under this category are apparently not common.

[1] W. H. Norton, *Jour. Geol.*, Vol. XXV (1917), pp. 182–85.

ACTION OF ICE

Intraformational contorted clays have, by various writers, been attributed to the action of ice but, as a rule, there has been little or no attempt to really analyze the structures involved. Salisbury and Atwood,[1] in their discussion of an extinct glacial lake near Devil's Lake, Wisconsin, figure and very briefly describe intraformational contorted clays. They say: "The grounding of an iceberg on the surface before the overlying layers were deposited, or the action of lake ice, may have been responsible for the singular phenomenon." In accordance with criteria set forth in the foregoing discussion of the Connecticut Valley clays, the writer believes that this corrugated zone must have resulted from differential movement after deposition of the overlying beds. The remarkable uniformity of thickness of the contorted zone; its relatively regular (nearly straight) upper surface; and the gently bent immediately overlying beds all strongly indicate that the corrugations developed under weight of the overlying beds. If the corrugations were caused by thrusting action of ice upon surface layers would not the contorted zone show notable variations in thickness and irregularity of its upper surface, and would not the overlying beds fail to show appreciable evidence of having been deformed? It is, however, conceivable that the corrugated zone may have resulted from differential movement brought about by the crowding action of ice against the upper portion of the whole body of clay, thus setting up a differential motion within its mass. Either this, or differential movement brought about under the action of gravity (in case the clays are at least moderately tilted), appears to have produced the corrugations.

J. Geikie,[2] in his description of the early postglacial deposits of the basin of the Forth in Scotland, says:

> Here and there also the beds (sands and clays) are much crumpled and confused, great sheets of clay being rolled over and over, and involving the associated sands for considerable distances. . . . These are exceedingly irregular, and are just of such a character as we should expect would result from the grounding of ice rafts.

[1] Salisbury and Atwood, *Jour. Geol.*, Vol. V (1897), p. 143.

[2] J. Geikie, *The Great Ice Age* (1894), pp. 271–72.

Such contorted zones were quite certainly produced before the overlying clays were deposited, as proved by the notable variation in thickness of the contorted zone, its very irregular upper surface, and the manner in which the perfectly undisturbed overlying clays were laid down on the irregular surface.

W. A. Johnston[1] has described and figured an interesting case of notably crumpled sand forming a zone of variable thickness under till near Fort Frances, Ontario. He says that the crumpling of the sand was due to the over-riding action of glacial ice.

DIFFERENTIAL WEIGHTING

Kindle,[2] in his discussion of deformation of unconsolidated beds on the Avon River, Nova Scotia, describes "a section of finely laminated horizontal silts, which, for a thickness of one foot or more near the middle, have been distorted into a highly convoluted zone." He advances the hypothesis of differential weighting to account for the phenomenon and says:

> If a heavy load of sand were deposited over a portion of an area in which very soft beds were interpolated between more coherent strata, the more mobile would be likely to squeeze outward away from the sand pressure toward an unsupported edge, if one were developed by stream or wave cutting. This might occur without disturbing firmer beds above and below through the more yielding character of the soft beds.

According to Kindle, current scour would remove the heavier and coarser beds, after which horizontal layers would be deposited over the disturbed beds. He describes experiments in which clay beds in glass tanks were notably deformed by differential weighting with shot.

Some reasons for thinking that the foregoing explanation is not applicable to the Avon River occurrence, and quite certainly not to intraformational contorted clays in general as typified by the Connecticut Valley occurrences above described, are as follows: (1) Quite generally, in nature, there is no evidence of anything like notable current scour, but rather there has been continual deposition of the clays; (2) in the experiments the surfaces of the deformed

[1] W. A. Johnston, *Can. Geol. Surv., Mem. 82* (1915), p. 43 and Pl. 8.

[2] E. M. Kindle, *Geol. Soc. Amer. Bull.*, Vol. XXVIII (1917), pp. 323–32.

zones are very irregular, while in nature they are usually very regular, or even straight, for long distances; (3) such regular surfaces could hardly have resulted from vigorous current scour because the contorted zones are usually remarkably uniform in thickness for long distances; (4) there is almost invariably no evidence for the present or former existence of materials of such arrangement and character directly over the contorted zones as to give rise to very appreciable differential weighting; and (5) the contorted beds are seldom very much softer or more mobile than the inclosing strata.

CRYSTALLIZATION AND HYDRATION

In certain types of rocks, like gypsum and salt, there is strong evidence for the development of intraformational deformative effects by crystallization (or hydration) after their deposition. In the Zechstein salt of Germany,

> where the enclosing rocks are undisturbed, the layers of brightly colored bittern salts and of gypsum often show a remarkable flexuous, sinuous, or disrupted character. . . . . In the Salina deposit of central New York, some of the alternating salt and gypsum layers occasionally show a pronounced flexing and overfolding, while others are wholly undisturbed.[1]

In his discussion of the salt beds of western central New York, Luther[2] has reproduced an interesting picture of a small sharply overturned fold of rock salt between practically undisturbed beds.

The above-described examples occur in regions of non-folded and non-faulted strata, and it seems quite certain that "the main force was the endogenetic one due to the crystallizing force of the salts and to metasomatic process" (Grabau after Arrhenius).

Very fine examples of corrugations and crenulations occur within the gypsum deposits at Hillsborough, New Brunswick. According to Ami[3] "the gypsiferous deposits present evenly banded structure, between which there occur neatly folded layers in the form of ribbon-like corrugations" (Fig. 22). Kramm[4] states that "the gypsum rests upon a bottom of anhydrite and reaches a maximum thickness of perhaps 125 feet," and that gypsum was derived by

[1] A. W. Grabau, *Principles of Stratigraphy* (1913), p. 757.

[2] D. D. Luther, *N.Y. State Mus. Rept. 50*, Part 2 (1896), Pl. 4.

[3] H. M. Ami, *Geol. Soc. Amer. Bull.*, Vol. XXV (1914), p. 37.

[4] H. E. Kramm, *Can. Geol. Surv., Guide Book No. 1*, Part 2 (1913), p. 364.

hydration of anhydrite, as can be observed in many places. Since the gypsum beds occur in a very shallow syncline, the highly crenulated intercalated layers cannot have been caused by regional folding. The cause was, no doubt, the force exerted within the whole mass as a result of the great expansion during the transformation of anhydrite to gypsum. Differential stresses and strains set up locally in the whole mass caused localization of the corrugations (Fig. 9).

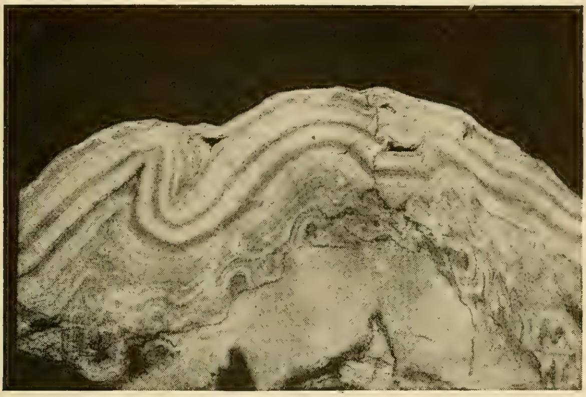

FIG. 9.—A specimen of gypsum from Hillsborough, New Brunswick, showing highly folded layers between less folded layers.

PRESSURE OF INTRUDING MAGMAS

Among the pre-Cambrian rocks of the Adirondack Mountains, New York, the writer has observed excellent examples of intraformational corrugations which are believed to have been direct effects of the pressure of magmatic intrusions. He has presented evidence[1] to support the view that the very ancient Grenville stratified series has never been subjected to severe regional folding throughout most or all of the Adirondacks. During the intrusion of the tremendous volumes of syenite-granite magma, the Grenville series was, however, badly cut to pieces so that many masses, both small and great, were tilted about in the rising magma and in many places subjected to notable differential pressure. The limestones, especially where they are near contacts with the syenite-

[1] W. J. Miller, *Jour. Geol.*, Vol. XXIV (1916), pp. 595–96.

granite, much more commonly exhibit local corrugations or crumplings than the other more rigid strata. Where a mass of the Grenville strata contains zones of well-bedded limestone intercalated between more rigid strata, and the whole has been subjected to differential pressure by the invading magma, the limestone layers have not uncommonly become contorted by differential movement within the mass while the adjacent beds above and below have been deformed little or not at all. In Figure 10, which well illustrates such a phenomenon in northern New York, the contorted beds of

FIG. 10.—Crumpled beds of impure, thin-bedded, crystalline limestone between beds of only slightly disturbed garnetiferous gneiss north of Hermon, St. Lawrence County, New York.

very plastic impure limestone lie between heavy beds of rigid garnetiferous gneiss. This contorted limestone and its associated gneiss form part of a long narrow body of Grenville strata which was included in, and subjected to differential pressure by, a large body of granite magma, causing the more plastic limestone beds to crumple.

Spurr,[1] in his discussion of the Silver Peak region of Nevada, publishes a fine picture of intraformational contorted strata which occur on Mineral Ridge. In this region large volumes of granite magma invaded and cut to pieces Paleozoic strata made up of

[1] J. E. Spurr, *U.S. Geol. Surv. Prof. Paper 55* (1906), p. 108 and Pl. 21.

a comparatively thick series of thin-bedded, shaly, and calcareous sediments intercalated with beds of pure limestone, now metamorphosed into marble. The thin-bedded sediments are sometimes carbonaceous, sometimes streaked with sandy material. . . . The limestone-slates are contorted on a minor scale. Most of this crumpling was probably due to the intrusion.

Beyond the last sentence quoted, Spurr says nothing regarding the cause of the intraformational crumpling. The available data rather clearly indicate that these corrugations, like those above described as occurring in northern New York, have been caused by the magmatic intrusion where a block of strata was more or less completely surrounded by the magma and subjected to differential movement, causing the more yielding layers to crumple.

Between 5 and 6 miles north of Northampton, Massachusetts, the writer has observed excellent examples of local contortions within the Leyden argillite (Paleozoic) formation near its contact with a basic phase of the Williamsburg granite. For about 2 miles parallel to the contact, irregularly distributed contortions are highly developed in the argillite for 10 to 20 rods out from the contact. Beyond that they rapidly diminish to disappearance. From the field evidence it seems clear that the corrugations resulted from differential movements within the argillite, caused by the shouldering pressure of the rising magma.

ACTION OF MAGMATIC INJECTION

In certain regions magmatic injection schists and gneisses contain local portions which are highly contorted. Many observations of such phenomena have been made by the writer in his study of the Adirondack Precambrian rocks. The following brief description of a certain district may best serve to illustrate the main principles involved. Extending 2 miles northeastward from just north of the village of Russell, St. Lawrence County, New York, there is a wide belt of mixed rocks containing fine exposures of amphibolite and garnetiferous gneisses intimately cut and injected, mostly parallel to the foliation, by moderately coarse-grained granite and pegmatitic granite, the whole mass being conspicuously banded. Just north of the village most of the mixed rock is notably contorted, while one-fourth to one-half of a mile farther east most of the rock is relatively straight-banded, but contains local highly contorted

zones. Still farther east the mixed rocks are nearly all straight-banded. It is believed that, during the forcing in of the magma, the whole mass of rock was notably plastic, and that local differential movements within the mass, caused by unequal pressures of the rising magma, resulted in the local corrugations.

MAGMATIC FLOWAGE

Finally, in our discussion of intraformational contorted rocks, differential magmatic flowage should be mentioned as a cause. Within certain areas of plutonic igneous rocks which exhibit primary foliation, there are not uncommonly local zones or bands in which the gneissoid structure, accentuated by dark minerals, appears to be irregular, wavy, or even contorted. The writer's experience in the Adirondacks shows[1] such local, contorted, primary flow-structures to be very common there, especially in the great syenite-granite series, and it is believed that they are essentially the result of varying magmatic currents under differential pressure, principally during a late stage of magma consolidation.

Lawson[2] has noted similar structures within certain granites of the Rainy Lake region of Ontario. He says: "The lines of streaking are very often not straight, but are wavy or contorted, sometimes intricately so, and are evidently due to slow movements in the magma prior to final consolidation."

[1] W. J. Miller, *Jour. Geol.*, Vol. XXIV (1916), pp. 611–12.

[2] A. C. Lawson, *Can. Geol. Surv., Mem.* 40 (1913), p. 93.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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Trondhjem, Norway

(Continued from page 649 of Vol. XXIX)

V

THE INFLUENCE OF PRESSURE

A

The dependence of the melting point on uniform[1] pressure is designated, as is well known, by the formula established by Clausius-Chapeyron:

$$\frac{\Delta T}{\Delta P} = 10.333 \cdot \frac{T(v_{liquid} - v_{solid})}{E.\ q.},$$

$\frac{\Delta T}{\Delta P}$ designating the alteration of the melting point in C° per increase of atmospheric pressure, T the melting point in absolute temperature (starting from $-273°$), q the latent melting heat in gr. cal. pr. gr., v the specific volume (in cm^3 per gr.) at the melting point—$v_{liq.} - v_{sol.}$ accordingly meaning the difference of specific volume between the liquid and the solid phase at the melting point—and $E = 425$.

In by far the most substances $v_{liq.} - v_{sol.}$ is positive at common and at moderate pressures. Accordingly the minerals, when melting, must, as a general rule, expand in volume or become of lower specific gravity. The case is entirely the reverse of that of ice and of bismuth.

[1] Within a liquid, such as a magma, also in the case that more or less mineral has already crystallized, the pressure always becomes uniform or hydrostatic, and in this case the formula quoted is applicable. Quite different is the case of *non-uniform* compression (and stress) in the solid phase. I beg to refer to a series of publications of recent years (see the review of John Johnston in this Journal, XXIII [1915], p. 732).

G. Tammann, as is well known, has pointed out that for many salts, $v_{liq.} - v_{sol.}$ decreases with increasing pressure so that, when the pressure is extraordinarily high, for instance 5000–10,000 atmospheres, it approaches zero; at still higher pressure the difference may be negative. However, this is not the case of substances in general. Thus P. W. Bridgman[1] has experimentally ascertained that, in a great many substances (metals and some salts, etc.), on pressures rising to 12,000 atmospheres (corresponding, for a magma, to a depth of about 40 kilometers), $v_{liq.} - v_{sol.}$ remains positive—indeed with gradually (somewhat) decreasing magnitude for increasing pressure. Some substances, even at the enormous pressures just mentioned, show but an inconsiderable decrease of the difference of volume, and J. Johnston and L. H. Adams[2] showed, for a number of metals, under a pressure of up to 2000 atmospheres (corresponding, for a magma, to a depth of about 7.5 kilometers), a rectilinear course of the difference of volume.

Under a pressure of one atmosphere all the silicate minerals hitherto examined show, at room-temperature, a lower specific gravity for the glass, that is the extreme viscous fluid phase, than for the crystalline, that is the solid phase.

According to what we have stated above, we must take it for granted that for rock-forming minerals $v_{liq.} - v_{sol.}$ is in all cases positive, and that the difference of volume existing for a pressure of one atmosphere will remain nearly constant, at any rate down to depths of a few kilometers, and that even to depths of 5 or 10 kilometers it will show practically no or only a little decrease.

As far as the common rock-forming silicate minerals are concerned, the *latent melting heat* is very high throughout. In fact for minerals melting at about 1200° to 1400° or 1500°, it amounts to about 90 or 100 gr. cal. pr. gr.—for some a little more and for some a little less.[3]

[1] *Proc. Amer. Acad.*, XLVII (1911–12) and *Physic. Rev.*, III (1914).

[2] *Zeits. f. anorg. Chemie*, 72 (1911), and *Amer. Jour. of Sci.*, XXXI (1911).

[3] As for anorthite (melting point 1550°), diopside (1391°), åkermanite (about 1310°) and fayalite (about 1075°), I have in earlier publications (Silikatschmelzlös. II [1904], with correcting calculation in my publication on slags in Doelters, *Handb. d. Mineralchemie*, I [1912], p. 942) determined the latent melting heat at respectively about 105, 94, 90, 80 cal., with an error limit of ±15 or 20 cal. For anorthite Bowen

Thus the divisor of the formula becomes very great, and consequently the melting point of the silicate minerals rises but very little on increasing pressure.[1] As an illustration I cite a case treated in my publication just quoted:

For a mineral with melting point = 1200°, melting heat = 100 cal., density in the solid phase = 3.000 and in the fluid phase = 2.887, $v_{liq.} - v_{sol.}$, at the melting point accordingly amounting to 0.013 or 3.9 per cent we calculate the melting point at higher pressures:

Pressure	Depth below the Surface	Melting Point
1 atmosphere....................	0 kilom.	1200°
270 atmospheres.................	1 kilom.	1201.3°
2700 atmospheres................	10 kilom.	1213.5°
10,000 atmospheres.............	37 kilom.	1250°

We have assumed, in this instance, in accordance with an early examination carried out by C. Barus,[2] a percentage value of 3.9 per cent, for the difference (at the pressure of one atmosphere) between the specific volume in the fluid and in the solid phase of the melting point, and we assume also the same value at higher pressure.

A series of determinations of glass and of crystalline substance at room-temperature (15° or 20°) show, for rock-forming minerals and for rocks, the following percentage differences of specific volume:[3]

In some cases only about 3 per cent (2.9–3.5 per cent), in most cases between 5 and 8 per cent, exceptionally up to 10.6, 11.4, and in a single case 13.6 per cent.[4]

(in his study on plagioclase, *loc. cit.*) has calculated 104.2 cal. (I found 105 cal. ± 20 per cent.) For diopside W. P. White (*Amer. Jour. Sci.*, XXVIII [1909], p. 486, footnote), according to a preliminary determination, states 106 ± 15 cal. (I found 94 ± 15 per cent.)

[1] I beg to refer to my statement in *Tscherm. Mitt.*, XXVII (1908).

[2] *Phil. Mag. London*, XXXV (1893), and *U.S. Geol. Surv. Bull. 103.*

[3] Most of these statements are grouped from Doelters, *Handb. d. Mineralchemie*, I (1912), p. 672.

[4] The last named value concerns $CaMgSiO_2O_6$ with density of the mineral diopside = 3.275, and of the glass = 2.830 (Allen, White, etc., *Amer. Jour. of Sci.*, XXVII [1909], $v_{liq.} - v_{sol.}$ accordingly = 0.3533 − 0.3053 = 0.050.

These figures, however, cannot be transferred so as to be applied at the melting point without being corrected, as the crystalline and the glassy phase will, as a general rule, differ a little as to volume dilation.

The only precision investigation known to me of the specific volume of a silicate at the melting point, has been carried out by A. L. Day, R. B. Sosman and J. C. Hostetter,[1] who determined for a diabase:

At 20° in the crystalline phase dens. = 2.975 (specific volume = 0.3362) and in the glassy phase dens. = 2.763 (specific volume = 0.3620), the percentage difference at 20° accordingly, amounting to 7.1 per cent, the glass being taken as the starting point.

This percentage difference increased at the melting point to 9.1 as a minimum and 10.9 as a maximum, and next to the last figure, accordingly to about 10.5 per cent corresponding to a difference = *ca.* 0.041 of the specific volume.

From what we have stated above, we take it for granted that, at the melting point of the common rock-forming minerals (melting at about 1200–1500°), $v_{liq.} - v_{sol.}$ will, as a general rule, vary between the limits of about 0.015 and 0.045. Assuming a melting heat of 100 cal. and a melting point of respectively 1200° and 1500°, we shall have, for a pressure of 1000 atmospheres, corresponding to a depth of about 3.7 kilometers, a rise of temperature of respectively about 5–6° and about 15–18°. That is to say, in igneous flows, at depths of up to 0.5 or 1 kilometer, the melting point of the different minerals only rises between about 1° and about 4 or 5°, while in deep-seated rocks, in which the crystallization takes place at depths of 5, 10, or 15 kilometers, there may be involved a rise varying respectively between about 6° and 30°, between about 12° and 40°, and between about 15 or 20° and 60°.

Thus, even in deep-seated rocks crystallizing at very great depths, the rise of the melting point is rather inconsiderable. And it should be particularly emphasized that the *difference* of rise of the melting points of the various minerals crystallizing in one and the same magma, will only amount to some few degrees; even in deep-seated rocks the difference is rather small, in fact rarely amounting to more than 10, 20, or perhaps in some cases 40°.

[1] *Amer. Jour. of Sci.*, XXXVII (1914).

As to the *dislocation of the eutectic* by uniform pressure, H. W. Bakhuis Rooreboom[1] has stated that in this case also the formula of Clausius-Chapeyron is applicable. The rise of temperature of the binary (and the ternary) eutectic of the rock-forming minerals by pressure may consequently be measured by the same *small* measures that have just been indicated for the minerals themselves.

Moreover, it is to be noted that the tangent to the melting curve near the origo (respectively 100 per cent *a* and 100 per cent *b*) is determined by the factors: T (absolute temperature), q (melting heat), and the electrolytic dissociation which three factors are but little dislocated by pressure, and finally the molecular weight which is constant if no polymerisation takes place. In other words, the melting curve in a binary system (Fig. 50) near the origo will, at high pressure, take a course parallel to that of the melting curve at low pressure. The further course of the melting curve is also essentially determined by the constants just mentioned, which are generally very little dislocated by pressure. This relates to the general experience that pressure has but little influence on the solubility of the mutual solutions, provided that no vapor phase is present.

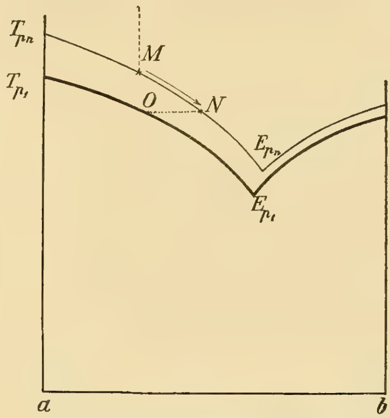

FIG. 50.—Illustrating the unessential dislocation of the composition of the binary eutectic by uniform pressure.

T_{p_1}, T_{pn} = melting point and E_{p_1}, E_{pn} = binary eutectic by respectively low and high pressure.

The contents of *a* and *b* at the intersecting point of the curves, in other words the composition of the binary eutectic, (E_{p_1} at low pressure, and E_{pn} at high pressure) will accordingly be but very little dislocated by pressure. And this accords with the fact that the temperature of E_{pn}, as just stated, is only very little higher than that of E_{p_1}. This reasoning can also be extended so as to be applied to the ternary and still more complex eutectics.

[1] *Heterogene Gleichgewichte*, II (1904), p. 715.

The error made by transferring the determination of the *composition of the eutectic on a pressure of one atmosphere*, to be applied also to the *pressure prevailing during the crystallization of the eruptive rocks*, will accordingly be *rather unimportant provided that the minerals involved are formed independently of pressure.*

I have demonstrated this fact by some petrographic instances in my publication in *Tscherm. Min. Petrogr. Mitt.*, XXV (1906), and XXVII (1908). I will here only point out that the analyses of the final eutectic quartz: feldspar-product from igneous flows, formed at a comparatively low pressure, accord within the limits of error exactly with the corresponding final product from granitic deep-seated rocks and also with the graphic granite in the Archean granite-pegmatite dikes formed at very great depths (see the analysis No. 1–40). And I deem it right to employ the experimentally determined eutectic Qu:An, at a pressure of one atmosphere, for parallellism with the eutectic Qu:Ab in deep-seated rocks or granite-pegmatite dikes (Fig. 3).

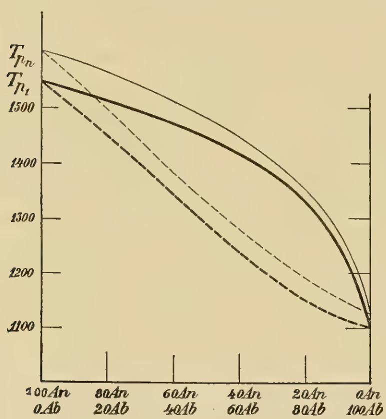

FIG. 51.—Illustrating the unessential dislocation of the *horizontal* difference between the liquidus and the solidus curve of the An : Ab-system by low and high pressure.

T_{p_1}, T_{pn} = smelting point by respectively low and high pressure.

The same general reasoning as to the inconsiderable influence of pressure on the dislocation of the melting point and on the eutectic may be transferred, in all essentials also to *mix-crystal systems*, or at any rate, to the continuous mix-crystal systems of type I.

For example, let us consider Ab:An. Even if the melting point of An should, at high-pressure, rise a little more or a little less than of Ab, it must be presumed a priori that the course of the liquidus and the solidus curves, and, what is petrographically of the greatest importance, the *horizontal distance between the liquidus and the solidus curves*, will remain almost the same (Fig. 51) at a high pressure

(p_n) as at a low one (p_i). This is also verified by petrographic experience. Thus in effusives and dike-rocks with a proportion Ab:An, fixed from the analysis of the whole rock, the mix-crystal first separated had nearly exactly the same composition as in a melt of Ab+An crystallizing at a pressure of one atmosphere.[1]

B

The formula of Clausius-Chapeyron quoted (p. 611) is to be applied also to the dislocation, at uniform (hydrostatic) pressure, of the *inversion point* between two reversible solid phases of one and the same substance.

The volume difference $v_1 - v_2$, in this case, involves the difference between the solid phases stable at higher and lower temperature, and the melting heat must be replaced by the inversion heat.

Also here $v_1 - v_2$ is in most cases positive, and only exceptionally negative.[2]

The *inversion heat* between two solid phases of one and the same substance is, so far as we now know, always positive and generally very small, sometimes low even almost to zero, and in most cases it amounts only to a small fraction of the melting heat.[3]

For metals, sulphides, silicates, etc., the divisor of the temperature: pressure formula thus becomes, as a general rule, very small,

[1] I refer, on this subject, to a comparison between my account in *Tscherm. Mitt.*, (1905), of the mix-crystal system Ab:An in igneous rocks and the diagram of Bowen (cf. Fig. 2, dating from 1912–13) for the Ab:An melt at the pressure of one atmosphere. The analyses of the plagioclase first separated in the rocks concern partly plagioclase somewhat zonally constructed, and partly plagioclase that has grown a little poorer in An and richer in Ab on account of partial equilibrium of the solid and the liquid phase. The plagioclase mix-crystal first separated in andesites, dacites, etc., will, accordingly, have been somewhat richer in An and poorer in Ab than is indicated in the analysis tables on pages 503 and 512 in my publication in *Tscherm. Mitt.*, XXV (1905).

[2] As an instance of negative $v_1 - v_2$ is mentioned: The density of the three modifications of Ca_2SiO_4 amounts to: of α (at a high temperature) = 3.27, of β = 3.28, and of γ (at a low temperature) = 2.97. The density of common stannum is = 7.3, that of the gray tin formed at a low temperature (undercooled much below +20°) is only = 5.8. Both in the passage from β to γ-Ca_2SiO_4, and from the common white stannum to the gray one, so great an increase of volume takes place that the substance is disintegrated by itself.

[3] However, to this rule also there are some exceptions. The most striking instance is formed by lithiumsulphate having an inversion heat even five times greater than the melting heat (Hüttner und Tammann, *Zeit. f. anorg.*, Ch. 43 [1903]).

and consequently the inversion temperature, even if v_1-v_2 only amounts to a medium positive value, will have a not quite inconsiderable rise on increasing pressure. And if v_1-v_2 is considerable (and positive) the *rise of inversion temperature owing to pressure will be exceedingly great.*[1]

This has been experimentally examined for monoclinic and orthorhombic sulphur (monocline S, on pressure of one atmosphere having its melting point at 119.25°, density = 1.98, melting heat, = 12.5 cal. 1 inversion temperature between monoclinic and orthorhombic S, on pressure of one atmosphere = 95.6°, inversion heat = 2.52 cal., density of orthorhombic S = 2.07 and melting point = 112.8).

On pressure the inversion temperature between monoclinic and orthorhombic sulphur rises more than the melting curve of monoclinic sulphur. The two curves intersect at a pressure of 1320 kilogrammes pr. cm² (= 1275 atmospheres) and at a temperature of 151°, and at *still higher pressure only orthorhombic sulphur may be formed.*[2]

Accordingly it will not be surprising that, in the case of a rock-forming mineral which at low pressure has an α-form (at high temperature) as well as a β-form (at lower temperature), it should always be the β-form,[3] or the form stable at lower temperature, that crystallizes in eruptive rocks formed at high pressure.

Let us consider particularly some of the most important modifications of SiO_2:

The inversion from α-cristobalite into α-tridymite at 1470 ± 10°.[4]

The inversion from α-tridymite into α-quartz at 870 ± 10°).[4]

[1] Therefore, the doctrine, advanced by me in 1908, of the inconsiderable rise of the *melting* point of silicate minerals cannot also, as a general rule, be transferred to the *inversion* point. I refer, on this subject, to the instructive remarks, made by V. M. Goldschmidt, *Die Kontaktmetamorphose im Kristianiagebiet* (1911), p. 112, and by C. N. Fenner, *Jour. of the Wash. Acad. of Sci.* (1912), 2.

[2] See G. Tammann *Krystallisieren und Schmelzen* (1903), and several publications by Roozeboom reviewed in Doelter's *Phys.-chem. Mineralogie* (1905), p. 31.

[3] According to the terminology used by Boeke and by many other mineralogists, I employ α to designate the modification stable at a higher temperature, β and γ to designate the modifications stable at lower temperatures. To avoid misconception, it should be noted that some investigators, among them Wright and Larsen, have employed quite the reverse terminology (α designating lower, and β higher temperature).

[4] C. N. Fenner, *Amer. Jour. of Sci.*, XXXVI (1913).

The inversion from α-quartz into β-quartz at 575± 2°.[1]

According to the statement made by A. L. Day, R. B. Sosman, and J. C. Hostetter[2] the specific volume of β-quartz is at 20° 0.3775 (= density 2.649), but rises by heating, and at 561°, or just below the inversion point, it has risen to 0.3922. At the inversion point there is a sudden rise, which, however, is not precisely stated, and then we pass on to α-quartz at 585° with a specific volume of 0.3972.

According to the statements of F. E. Wright and Esper L. Larsen the inversion heat, when β-quartz is transformed into α-quartz, amounts to 4.3± 1 cal. If we set the volume difference at the point of inversion at 0.003 and the inversion heat at 4.3 cal., there is a rise of 0.015° per atmosphere, which makes at a pressure of 1000 atmospheres, corresponding to a depth of about 3.7 kilometers, a rise of about 15°. This affords a measure for the order or quantity which has to be taken into account. Accordingly the difference between α-quartz and β-quartz, if depths of more than 5 kilometers are not involved, can, at any rate with only a little modification, be employed as a geological thermometer.

As to the relation of inversion point and pressure between α-quartz and tridymite the case is quite different. At room temperature tridymite has a specific volume of 0.4329 (density = 2.31, medium of 2.282 and 2.326) and β-quartz a specific volume of 0.3775 (density = 2.649); $v_1 - v_2$ accordingly amounts to 0.0554, which is a very high value. By heating, β-quartz, as has just been mentioned, expands its volume considerably and then changes into α-quartz, which, according to the statements of Day, etc., has at 850° a specific volume of 0.3957. According to the law of the expansion of bodies by heating, tridymite also must expand its volume at higher temperature, but how much is not stated. If we estimate its specific volume at 875° at 0.445, the volume difference $v_1 - v_2$ at 875° will amount to 0.05 (or perhaps a little more).

The inversion heat is not stated, but must be supposed to be tolerably low. A rough estimate, rating the inversion heat at 10 and 5 cal., respectively, gives a rise of inversion temperature per

[1] F. E. Wright and E. S. Larsen, "Quartz as a Geologic Thermometer," *Amer. Jour. of Sci.*, XXVII (1909).

[2] *Amer. Jour. of Sci.*, XXXVII (1914).

atmospheric pressure of respectively 0.115 and 0.23°. A corresponding rough calculation has been made by Fenner,[1] who presumed $v_1 - v_2 = 0.057$ (as at room temperature) and inversion heat = 15 cal., which makes a rise of temperature per atmosphere of 0.105°. Starting from these figures (15, 10, 5 cal.) we should have, on a pressure of 270 atmospheres (or at the depth of 1 kilometer), a rise of the inversion point of respectively 28, 38 and 76°, or from 875° to respectively 908, 913 and 951°—and it may be that even the last number is too low an estimate. On the pressure prevailing at the depth of a few kilometers, the inversion point quite certainly will most likely prove to be considerably above 1200°.

The binary eutectics Qu:Or and Qu:Ab, at a pressure of one atmosphere, I estimate at about 1075°–1100°, repectively 975°–1000°. The ternary eutectic Qu:Or:Ab must lie somewhat lower, probably at about 950° or 925°.

If we choose for instance a common granite, quartz porphyry, or rhyolite, the final crystallization must here take place as a complex eutectic Qu:Or:Ab+An, with a little ferric oxide and Mg, Fe-silicate, at a pressure of one atmosphere at a temperature of presumably about 900°-950°. And even if there occurs some surplus quartz, so that the crystallization of this mineral begins at a comparatively early stage, still the first crystallization of SiO_2 will scarcely take place at a higher temperature than 950° or 1000°. These values of temperature reckoned on the pressure of one atmosphere must certainly be increased somewhat, but only a little, for crystallization at great depth and under high pressure, but, as we shall mention later, must be decreased by the content of water, etc., especially in the granitic deep-seated magma.

As, on the other hand, the temperature of the inversion point between α-quartz and tridymite rises so considerably, SiO_2 will never crystallize in deep-seated rocks as tridymite, but always as quartz, and this quartz in granite, quartz-porphyry, and graphic granite is, as pointed out by Wright and Larsen, always an α-quartz.

Tridymite as a primary[2] formation in igneous rocks is, as is well known, limited to certain rhyolites, trachytes, andesites, etc.,

[1] *Jour. of the Wash. Acad. of Sci.*, 2 (1912), p. 479 and *Amer. Jour. of Sci.*, XXXVI (1913), p. 347.

[2] The hydrothermal formation of tridymite is here left out of consideration.

consequently to effusive rocks and to some dike rocks crystallized at a small depth. The crystallizing temperature will here have been above, probably indeed only a little above, the inversion point between α-quartz and tridymite in force at the pressure in question, and accordingly at depths of some hundred m., viz., at about 900° or perhaps a little higher.

By stating the depths at which SiO_2, in the effusives and dike rocks here mentioned, occurs as quartz or as tridymite, our knowledge of the influence of pressure on the rise of the inversion point between α-quartz and tridymite will be increased. Fenner (*Amer. Jour. of Sci.*, XXXVI, p. 348) describes a volcanic rock in which quartz phenocrysts were first formed and were afterward transformed into tridymite. Fenner suggests the explanation that the quartz phenocrysts were formed at higher pressure a little below the inversion point in force at the pressure in question, and that the magma with its phenocrysts was afterwards brought nearer the surface, viz., to a diminished pressure, lying a little above the inversion point at the given temperature. The phenocrysts of α-quartz first formed at the greater depth must consequently now be transformed into tridymite. Fenner, however, expresses some doubt as to this explanation, which, after all, in my opinion, is the natural one.

According to what has been stated by Wright and Larsen, the quartz in the graphic-granite from granite-pegmatites was originally formed as α-quartz, and accordingly at a relatively high temperature, viz., between the inversion point between β- to α-quartz and α-quartz to tridymite. But, besides, there sometimes occurs, in the granite-pegmatites, quartz that "in all probability has never been heated above the inversion temperature between α- and β-quartz." "These large masses of quartz were in certain cases definitely stated by the field relations to be the last portions of the pegmatite to crystallize out." This β-quartz which is formed below the inversion point between α- and β-quartz, and the formation of which, at the enormous pressure, must have taken place at a temperature below 600 or 625°, must be supposed to have been separated from a particular solution of SiO_2+H_2O (see following chapter on the influence of the light volatile compounds).

According to the investigations made at the Geophysical Laboratory in Washington, the inversion point between pure $\alpha = CaSiO_3$ (*pseudowollastonite*) and $\beta = CaSiO_3$ (*wollastonite*) has been stated at about 1200°. Some amount of $MgSiO_3$ entering isomorphously into the silicate makes the inversion point rise; thus about 6 per cent $MgSiO_3$ brings about a rise up to 1300° and 17 per cent $CaMgSi_2O_6$ (= *ca.* 8 per cent $MgSiO_3$) even up to 1345 ± 10° C.[1] The inversion point of the mineral wollastonite occurring in the contact zones, containing as as general rule a little $MgSiO_3$, must, accordingly, be estimated, at the pressure of one atmosphere, at about 1250–1300°, and at a high pressure even a little higher temperature must be presumed, though, on account of the small difference of density between the two forms, the rise will probably be quite inconsiderable.[2]

As will be brought out in a later paper, the *eruption* of the magmas, as a general rule, took place at a temperature which was for the deep-seated rocks almost exactly *identical with the temperature of the beginning crystallization.* For the porphyry rocks we may in many cases assume a temperature of the eruption even somewhat below that of the beginning crystallization.

If we leave out of consideration the peridotites, anorthosites, and analogous anchi-monomineral deep-seated rocks, the *eruption temperature*, accordingly, must only exceptionally have been so high as about 1300°. For many anchi-eutectic rocks, I estimate it at about 1250°, and for granitic rocks, even much lower still, as 1000° or somewhat less. Thus, it is easily explained that in the contact zones there always occurs wollastonite and never pseudowollastonite.

$MgSiO_3$.—According to the investigations made by O. Andersen and N. L. Bowen[3] $MgSiO_2$ has, at usual pressure, no true melting point, as, at 1557°, $MgSiO_2$ is divided into solid Mg_2SiO_4 (forsterite) and liquid. The weight proportion of the two phases is 5.5 per cent

[1] T. B. Ferguson and H. E. Merwin, *Amer. Jour. of Sci.*, XLVIII (1919), p. 165, and the earlier investigations here cited.

[2] White and Larsen, *Amer. Jour. of Sci.*, XXVII (1909), p. 421; cf. V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristianiagebiet" (1911), p. 110.

[3] *Amer. Jour. of Sci.*, XXXVII (1914), and *Zeits. f. anorg.*, Ch. 87 (1914).

forsterite to 94.5 per cent fluid. With continued heating the forsterite dissolves in the course of time, so that all is transformed into fluid at 1577°.

On cooling a melt of $MgSiO_3$ there first crystallizes (at 1577°–1557°) a little forsterite, which on continued (and slow) cooling is resorbed under new formation of solid $MgSiO_3$ (at high temperature clinoenstatite).

The inversion point, at a pressure of one atmosphere, between clinoenstatite and enstatite amounts to about 1100°. The point cannot be settled exactly. The above reference to the treatise of Andersen and Bowen is for pure $MgSiO_3$ (at one atmospheric pressure).

For (Mg, Fe) SiO_3, (Mg, ^{Fe}) SiO_3 and $FeSiO_3$ the following must be taken into consideration:

Mg_2SiO_4 has melting point 1890°.

Fe_2SiO_4 has melting point about 1100°.

For the intermediate mixtures there are intermediate melting point intervals (Fig. 22).

Fe_2SiO_4 and Mg_2SiO_4 with relation about in the middle between Mg and Fe, has a considerably lower melting point interval than 1550°, and consequently cannot be separated in the solid face at the first mentioned temperature from a (Mg, Fe) SiO_3 melt. This makes it probable that the splitting by one atmosphere's pressure of solid pure $MgSiO_3$ into olivine-mineral and fluid may be transferred to (Mg, ^{Fe}) SiO_3 with only a little Fe, but not to metasilicate with predominant Fe or with a middle relation between Mg and Fe.

Clinoenstatite (respectively clinobronzite), as well known, sometimes occurs in meteorites, but has never been determined certainly in terrestrial igneous rocks. If the metasilicate in the rocks originally had existed in the clino-modification (clino-enstatite, -bronzite, -hypersthene) we might, according to the experiences from the meteorites, suppose that the original mineral, in any case, occasionally would still have been in existence. But while this, as far as we know up to date, never is the case, the explanation seems to be that the crystallization of the Mg, Fe-metasilicate in the common igneous rocks—of composition between 0.08 $FeSiO_3$, 0.92 $MgSiO_3$ and about 0.4 $FeSiO_3$, 0.6 $MgSiO_3$—always took place

for the existing pressure at a temperature lower than the inversion point between the clino- and the ortho-modification of the metasilicate. This view is strengthened by the fact that in the rocks where the metasilicate has crystallized at an early stage it shows the crystallographic contour of the orthopyroxene.

It is probable that the inversion temperature between the clino- and the ortho-modification rises not quite inconsiderably with the pressure. The difference in density between clinoenstatite and enstatite is indeed very little, but if the inversion heat is minimal, as only a small fraction of 1 cal., the inversion temperature will nevertheless increase not inconsiderably with the pressure. In the common anchi-eutectic norites, etc., the crystallization interval for the most part lies at about 1275–1200°, which must be lower than the inversion boundary at high pressure between the two Mg, Fe-metasilicate stages. In bronzite rocks and bronzite-carrying olivine rocks a not inconsiderably higher crystallization interval may be presumed, but even in these rocks we cannot observe any structural indication that here originally occurred a clino-modification.

By melting $MgSiO_3$ at 1557° to a liquid in connection with solid olivine—the latter only in a small quantity—and at 1577° only to a liquid, $v_1 - v_2$ will, in accordance with what happens in all previously examined silicates, doubtless be positive. That is to say, the "incongruent" melting point of $MgSiO_3$, in the same way as of other silicates, must be supposed to rise somewhat with the pressure. The splitting of $MgSiO_3$ to an olivine (very poor in FeO) in the igneous rocks might thus have taken place at a temperature somewhat above 1557°. But the crystallization of the hypersthene-bearing gabbros, syenites, granites, etc., occurred, as just mentioned, at a considerably lower temperature. The conclusion of this, according to my view, is that the proved crystallization of forsterite in a melt of $MgSiO_3$ at a pressure of one atmosphere cannot be transferred to take place at the crystallization of the bronzite- or hypersthene-bearing deep-seated rocks. I cannot agree with more of the opinions maintained by Andersen and Bowen (*loc. cit.*) and Bowen[1] since these investigators have not taken into consideration the influence of pressure.

[1] The crystallization of haplobasaltic and haplodioritic magmas (1915), and The later stages of the evolution of the igneous rocks (1915).

As an argument for the primary crystallization of olivine with following resorbtion of olivine under new-formation of orthopyroxene, several investigators have referred to the well-known kelyphitic or coronation zones around olivine, with hypersthene in the inner zone facing the olivine. As stated above (Vol. XXIX, pp. 645–49) we are dealing here, however, with a reaction in the *solid* face between olivine and plagioclase at a maximum temperature of about 1250°–1200° and generally somewhat lower—thus at least 300° lower than the temperature (1557°) at which, under a pressure of one atmosphere, olivine may crystallize from a melt of $MgSiO_3$. The kelyphitic hypersthene zone next to the olivine may thus have nothing to do with the primary segregation of olivine from a melt of $MgSiO_3$ and the later transformation from olivine to orthopyroxene.

As maintained by Andersen (*loc. cit.* [1915], p. 453) the olivine, as a consequence of the splitting of $MgSiO_3$, in the orthopyroxene-bearing igneous rocks, should in every case have crystallized earlier than the orthopyroxene, and the crystallization of the olivine should have been finished even before the beginning of the solidification of the orthopyroxene. But petrographic investigation of rocks rich in orthopyroxene but poor in olivine, shows that this is not so. We refer to the facts mentioned above (Fig. 25).

The conclusion from this is that bronzite and hypersthene, under high pressure, in the common deep-seated magmas (norites, etc.), crystallized directly from the magma in the same way as the other common silicate minerals. How it may be with enstatite in an almost pure $MgSiO_3$ magma, remains, however, an open question. In the igneous rocks, indeed, we never find orthopyroxene with less than *ca.* 7 per cent $FeSiO_3$ (or more than 93 per cent $MgSiO_3$).

C

1. Many minerals, such as olivine, monoclinic pyroxene, the feldspars, spinel, magnetite, etc., may be formed in melts at a pressure of one atmosphere, as well as in effusives and in deep-seated rocks—consequently at low, as well as at middle high, and very high pressure.

2. Some minerals, as *melilite* for instance, which crystallize out of melts at a pressure of one atmosphere, occur, moreover, in effusive rocks (melilite basalts, etc.) and in certain dike rocks (as

alnöite), but on the other hand are not—as yet (1920)—known from deep-seated rocks.

If we compare a number of analyses of troctolite ("forellenstein" and feldspar-peridotites) with for instance the analyses of slags given in my work "Silikatschmelzlös," I, p. 16 (containing *ca.* 30–42 per cent SiO_2, 8–28 per cent AlO_3, 20–40 per cent CaO and up to 13 per cent MgO with some FeO, MnO, etc.), in which a melilite mineral (melilite-gehlenite) is crystallized, it is apparent that by re-melting at one atmosphere some of the deep-seated rocks mentioned, which consist only of olivine and anorthite-bytownite, they must recrystallize with more or less melilite besides several other minerals of which one is spinel (Vol. XXIX, p. 524).

Gehlenite occurs in some contact zones; it must consequently under certain conditions be formed at high pressure. And melilite occurs, as just mentioned, as a rarity in some dike rocks, which might have been solidified at a tolerably great depth, thus also at a tolerably great pressure.

It is worth noticing, however, that melilite, so far as known, is lacking in the common deep-seated rocks, and especially that, instead of a melilite mineral, we find in the troctolites the combination olivine and anorthite-bytownite.

A similar case is that of *leucite* which can crystallize in melts at a pressure of one atmosphere, and which occurs in many effusive and some dike rocks, but has only rarely been found in deep-seated rocks. When microcline and biotite are melted together in certain proportions, leucite results. And in many deep-seated rocks which by re-melting at one atmosphere would give leucite, we find instead of leucite other minerals, as microcline, biotite, etc.

3. On the other hand there are some minerals which in part preferentially and in part exclusively belong to deep-seated or other rocks formed at a very high pressure. As an instance we may choose *garnet*.

By re-melting garnet there results, as is known, not this mineral, but a mixture of other minerals, according to the composition of the garnet—melilite, anorthite, olivine, spinel, etc. On the other hand, we may get garnet by using certain chlorides, for instance $AlCl_3$, as the solution medium. Garnet—or at least some varieties

of garnet—may thus also be formed under high temperature at the pressure of one atmosphere.

Garnet occurs as a primary formation in some effusives and often in various deep-seated rocks. The mineral further is formed as known *inter alia* by contact-metamorphism and by intensive dynamo-metamorphism.

Amphibole, as is known, does not crystallize from anhydrous silicate melts at one atmosphere but it is generally supposed to be conditioned by high pressure. This depends rather certainly on the fact that the magmas only at high pressure may carry the sufficient quantity of water (or hydroxyl) which seems to be a constitutional component of amphibole.

Biotite has, as is known, been produced synthetically by melting with fluorides, and the magnesia-mica *phlogopite* has also been established as crystallized out of common anhydrous slags containing a little fluorine.[1] Phlogopite may thus be formed by crystallization of silicate melts at a pressure of one atmosphere. But common mica occurs in the igneous rocks preferentially in deep-seated rocks; it occurs also, however, in effusives. On the other hand, muscovite never occurs as a primary mineral in effusives, but occurs in certain granites and especially in granite-pegmatite dikes.

As we shall show later, in granites of exactly the same composition—excluding the original content of H_2O, etc.—hypersthene, biotite or muscovite may crystallize. Which of these three minerals is formed, may depend on the content of H_2O, etc., in the magma (when least, hypersthene is formed; when most, muscovite).

[1] See my cited treatises from 1884–85 and 1888–90. In slags from the Kafveltorp copper works (containing 41–46 per cent SiO_2, 8–11 Al_2O_3, 7–15 FeO including *ca.* 0.5 Fe_2O_3, 13–20 CaO, 10–18 MgO, a little ZnO, Cu_2S, etc., also 3–5 K_2O+Na_2O and a little F) there has crystallized 10–15 per cent mica, in great leaves up to 5–6 mm. in diameter, with the following characteristics: pseudohexagonale thin leaves, with just as good cleavage as natural mica; elastic flexible; pressure figure as in natural mica; prism angle *ca.* 121°; optical biaxial and negative; acute bisectrix almost perpendicular on 001, differing only by 1–1.5°; 2 V only a very few degrees; colorless; very vivid interference colors; very resistent to acids; chemical composition: 42.20 SiO_2, 11.30 Al_2O_3, 5.92 FeO (with a little Fe_2O_3), 22.93 MgO, 2.29 CaO, 1.40 ZnO, 0.33 Cu_2S (mechanical), total 86.37 per cent, rest *ca.* 13 per cent K_2O, Na_2O and F. The mineral is thus a MgO-mica rather poor in FeO and Fe_2O_3, viz., a phlogopite, whose content of H_2O (or HO) is replaced by another component, F.

The influence of pressure with regard to the minerals amphibole, biotite, and muscovite must then be indirect, since the formation of these minerals depends essentially on the magmatic content of H_2O, etc., which further, to a certain extent, depends on the pressure.

By great differences in pressure, H_2O content, etc., a magma otherwise of the same or almost the same chemical composition may give rise to the crystallization of totally different minerals or combination of minerals. P. Niggli, in his work (1920, p. 207) cited below, mentions as a typical instance of this the two rocks, (1) a durbachite (rich in biotite and hornblende and further orthoclase, plagioclase, a little quartz and titanite bearing boundary facies of granite), and (2) a glassy leucite basalt.

	1. Durbachite	2. Leucitebasalt
SiO_2	51.05	51.43
TiO_2	1.76	1.12
Al_2O_3	14.49	14.88
Fe_2O_3	4.16	6.30
FeO	4.37	3.14
MgO	8.16	6.67
CaO	5.11	5.01
Na_2O	1.85	1.83
K_2O	7.25	9.22
P_2O_5	0.70	0.51
H_2O	1.05	0.74
Total	99.94	100.85

1. Durbachite from Durbach, Schwarzwald. A. Sauer, *Mitt. Badische Geol. Landesanst.*, II, 1892 (1890). 2. Leucitebasalt from Gaussberg, Kaiser Wilhelm II Land. R. Reinisch, Deutsche Südpol-Exposition II (1), 1906.

Undoubtedly, on account of the high content of water, biotite and hornblende, and further orthoclase, have been formed in the durbachite, while on the other hand in leucite basalt which solidified at lower pressure leucite was formed instead of orthoclase and K_2O-rich biotite.

RS dissolved in silicate melts crystallizes at a pressure of one atmosphere as monosulphid (oldhamite, alabandine, sphalerite, pyrrhotine or troilite, etc.), but may at high pressure by pneumatolytic processes (in the crystallization of magmas as described by Brögger[1]

[1] *Zeits. f. Kryst. Min.*, XVI (1890), I, p. 161.

for the nepheline syenite-pegmatite dikes, further in contact zones, etc.), give rise to the formation of helvine (and danalite). At a moderately high pressure also some double-compounds of silicate and NaCl or Na_2SO_4 (sodalite, nosean and häuyn) crystallize. But these minerals—and according to my experience this is also true of scapolite—may not be reproduced by melting the respective silicate with admixture of NaCl or Na_2SO_4 at common low pressure.

In this connection it may be further mentioned that the magmatic crystallization of minerals as FeS_2 and $CaCO_3$ imply a high pressure.

This review proves that the formation of many minerals, or combinations of minerals, may take place at low pressure as well as at moderately high or very high pressure, and further, that the *determinations undertaken at one atmosphere pressure in regard to the eutectics and mix-crystal systems, so far as these minerals are concerned, may also be made valid with only slight corrections at high pressures,* even at the high pressure prevailing during the crystallization of the deap-seated magmas.

But this may not be applied to all minerals, or combinations of minerals. The formation of some minerals, as melilite and leucite, is favored by low pressure; the formation of other minerals, as garnet, is favored by high pressure. For some minerals, as especially muscovite, further H_2O-bearing biotite and hornblende, a more or less high pressure may be an indispensable condition for crystallization from the magma; indeed indirectly depending on the fact that the presence of sufficient H_2O in the magma implies a high pressure. For pyrite and calcspar, which at one atmosphere are dissociated by moderate heating, high pressure is necessary for their crystallization from the magma.

It is to be noted that *garnet* has a much *higher* density (Mg-Al_2–garnet 3.7–3.8, Ca-Al_2–garnet 3.9–4.0, Ca-Fe_2–garnet 3.8–4.1, etc.) than the combination of those minerals which result from re-melting it at one atmosphere. On the other hand, *leucite* has a much *lower* density (2.45–2.50) than the combination of those minerals, especially orthoclase (2.55) and the various K_2O-rich micas (2.76–3.0) which generally replace leucite in the deep-seated magmas. And *melilite* (2.90–2.93) has somewhat *lower* density than the combina-

tion of a medium mixture principally of olivine (3.22) and anorthite (2.765) which in most cases replace it in the deep-seated rocks.

In all of these three cases we thus observe the fact that a combination of minerals, respectively a single mineral (leucite, melilite) in the effusives are replaced in the deep-seated rocks by a single mineral (garnet), respectively a combination of minerals, characterized by *increased* density.

This recalls the well known "volume law" valid for dynamometamorphism, viz., that various minerals under high pressure form new combinations with the minimum total volume—a law whose physicochemical cause, moreover, is not exactly elucidated.

Since the above section, in the main, was written, in the winter 1919–20, a treatise on "The Mineral Facies of Rocks," by P. Eskola,[1] was published, wherein he tries to establish some (five) facies for the mineral combinations depending on the pressure not only for the metamorphic, but also for the igneous rocks. Eskola classes with the last, the facies of the igneous rocks formed under the highest pressure, among others those especially investigated by him, namely garnet-rich (with up to 75 mol. per cent pyrop-component $Mg_3Al_2 SiO_3O_{12}$) eclogites, which "occupy a volume about 15 per cent smaller than that of the corresponding gabbros." Eskola thus maintains the same views as those I have pointed out above. I call attention to this treatise, in which are given some new instances of the interdependence of the formation of certain mineral combination in the igneous rocks upon the pressure. Further on Eskola treats of the interdependence of the metamorphic new-formations upon the pressure, which matter I do not touch in this treatise.

[*To be continued*]

[1] *Norsk geol. Tidsskrift*, Vol. VI (1920).

EDITORIAL

There has come to the editors of this *Journal*, Volume 1, Number 1, of the Japanese *Journal of Geology and Geography*, issued under the auspices of the National Research Council, Department of Education, Japan. The journal is published in Tokio and will be issued as a quarterly. The *Journal of Geology* extends to this new confrère in the service of the earth sciences its hearty congratulations and good wishes. For a number of years Japan has been sending many of her young geologists to the United States for their special training, and the associations thus established have been mutually pleasant and profitable. The appearance of this journal, published in English, will extend and strengthen the comradeship in science between Japan and the United States and with all other English-speaking countries. The new journal consists in part of original contributions and in part of abstracts of articles appearing in other Japanese publications. Many of these cover articles originally published in Japanese that would not otherwise be utilizable by English-speaking readers. Many of the abstracts are prepared by the authors, and others come from such authoritative reviewers as Takeo Kato, well known to American geologists. While most of the abstracts are in English, one of them is in German.

E. S. B.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Miller, William J. "Geology of the Blue Mountain, New York, Quadrangle," *Bull. 192, N. Y. State Mus.*, 1916 (1917). Pp. 68, map 1, pls. 11, fig. 1.

The Blue Mountain Quadrangle in the Adirondack region lies in northern Hamilton County, N. Y. From oldest to youngest, the formations are: the Grenville series, limestones, and quartzites, followed by two small intrusions of anorthosite. The most widespread rocks of the region are syenite and granite with basic phases which are intrusive into both the Grenville series and the anorthosite. Following this came gabbro, still later pegmatite and a few dikes of diabase. Glacial and postglacial deposits complete the series. The rocks of the Grenville series are thought to be sedimentary. Twelve quartz-syenites are described, three of which are said to be "practically monzonites." The quartz ranges from 12 to 20 per cent, consequently the reviewer would prefer not to call them quartz-syenites, which name he would limit to syenites with less than 5 per cent quartz, but granites. In the reviewer's system ten of these rocks are classed in 226′, granites (or in limited sense monzo-granites), the remaining two are 226″ or quartz-monzonites. The basic phases of the syenite are 228, 328, 227″, 2212, 3211′, tonalites, quartz-monzonite, diorite, and monzo-diorite. Of fifteen granitic-syenites and granites, thirteen are 226′ (granites), one 126′ (a leuco-granite), and one near Daly's Moyie sill rock, at the intersection of Families 1, 2, 5, and 6′, in Class 2, Order 2. Of six "typical gabbros," one (No. 17) is a garnet-bearing melagabbro, and one (No. 52) is a garnet-bearing norite. The other four are said to contain oligoclase-labradorite and andesine-labradorite which, without further descriptions of the feldspars, prevents their classification.

Miller, William J. "Adirondack Anorthosite," *Bull. Geol. Soc. Amer.*, XXIX (1918), 399–462, figs. 3.

Miller takes exception to Bowen's statement (*Jour. Geol.*, XXV [1917], 242) that "Anorthosites are made up almost exclusively of the single mineral plagioclase." Bowen's statement is and is not true, depending upon whether the rock anorthosite or the anorthosite formation is meant. Hunt's original definition applied to a whole series of rocks which are "composed chiefly of a lime-soda feldspar, varying in composition from andesine to anorthite, and

associated with pyroxene or hypersthene. This rock we shall distinguish by the name of anorthosite. . . . . In some cases the . . . . dark mineral is entirely wanting." (*Geol. Canada*, 1863, 22.) According to modern petrographic usage the term anorthosite has come to mean a basic-feldspar rock, which is practically free from dark minerals, say with less than 5 per cent, yet the Canadian anorthosites are spoken of in the sense of Hunt. Bowen, therefore, if he speaks of the whole formation, is incorrect when he says that "Anorthosites are made up almost exclusively of the single mineral plagioclase," for as Miller shows, the dark mineral averages 10 per cent. He says, "The main bulk . . . . contains 5 to 10 per cent of minerals other than plagioclase . . . . in many places there are 10 to 20 per cent, or even more of dark mineral. It is also true that some portions of the mass contain less than 5 per cent of dark minerals. . . . . Conservatively estimated, I believe the average . . . . anorthosite carries fully 10 per cent of minerals other than plagioclase." Attacking Bowen's theory that the anorthosite may not have been at one time in a molten condition, Miller says: "The Adirondack anorthosite would have formed a melt of notably more complicated composition than the artificial melt with 10 per cent diopside and [it would have been formed] under deep-seated geologic conditions. Is it safe to say, therefore, that such a melt may not have been a true magma with a high percentage of liquid? . . . . Another important consideration is the almost certain presence of very appreciative amounts of dissolved vapors, particularly water vapor, in the magma. . . . . Also the presence of about 2 per cent iron oxide in the typical anorthosite should not be overlooked. . . . . All things considered, therefore, I not only think it very reasonable to apply the mutual solution theory to the anorthosite, but also to regard the anorthosite to have existed in magmatic condition at a moderate temperature." He says further: "I consider the main steps in the development of the anorthosite to have been as follows: First, intrusion of a laccolithic body of gabbroid magma . . . . second, relatively rapid cooling of the marginal portion to give rise to the chilled gabbroid border phase; and, third, settling of many of the slowly crystallizing femic minerals in the still molten interior portion of the laccolith, leaving a great body of magma to gradually crystallize into anorthosite. Thus, at the bottom, and probably nowhere visible in the field, lies a mass of pyroxenite or peridotite . . . . " (p. 457).

Miller says in reference to a syenite (p. 438), "Labradorite and andesine are always present and oligoclase usually." The reviewer must again make the statement which he has made a number of times before, that he doubts whether in rocks which are composed of crystals of a single generation, two different plagioclases can occur together except as zonal growth.

It is impossible in this abstract to give all of Miller's conclusions. Briefly they are:

The Adirondack anorthosite is a great laccolithic intrusive body—older than the accompanying granite-syenite series. The average rock contains fully 10 per cent of dark minerals, and is differentiated practically *in situ* from

an intruded gabbroid magma, developing a chilled gabbroid border facies and an upper zone of anorthosite from a magma which was to a very considerable degree at least, actually molten. The anorthosite-gabbro and gabbro associated with the anorthosite represent local differentiates. Syenite and granite are not differentiates from the anorthosite, although transition rocks (Keene gneiss) were produced locally by magmatic assimilation of still hot, but not molten, anorthosite by the syenite or granite magma.

MILLER, WILLIAM J. "Geology of the Schroon Lake Quadrangle," *Bull. 213, 214, N. Y. State Mus.*, 1918 (1919). Pp. 102, map 1, pls. 14, figs. 9.

The Schroon Lake quadrangle represents an area of about 215 square miles in the central eastern portion of the Adirondack mountain region. The oldest rocks are those of the Grenville series which were intruded by a relatively stiff gabbroid magma which differentiated and formed the anorthosite. The intrusion of the anorthosite lifted the Grenville strata but also engulfed fragments of it. Following this came the intrusion of the syenite-granite series which partially domed, partially broke and tilled, the Grenville. The metamorphism of the Grenville took place probably before or during the period of igneous activity. During the succeeding period of uplift there was great erosion and some igneous activity indicated by the intrusion of certain diabase dikes. In late Cambrian time a gradual submergence took place with deposition of sandstones and dolomites. A long period of erosion from Ordovician to late in the Mesozoic reduced the land to a peneplain rising to moderate heights above the general level, and this was followed by uplift and active erosion, which continues to the present time. During the Ice Age the entire area was covered by the ice sheet. Toward its close there was a subsidence of several hundred feet below the present level, and finally a differential uplift with greater elevation at the north.

MILLER, WILLIAM J. "Banded Structures of the Adirondack Syenite-Granite Series," *Science*, XLVIII (1918), 560–63.

Both assimilation and differentiation contributed to the banding.

MILLER, WILLIAM J. "Silexite: A New Rock Name," *Science*, XLIX (1919), 149.

The name silexite is proposed for any body of pure or nearly pure silica of igneous or aqueo-igneous origin which occurs as a dike, segregation mass, or inclusion within or without its parent rock. (See also "Pegmatite, Silexite, and Aplite of Northern New York," *Jour. Geol.*, XXVII [1919], 28–54.)

MOORE, E. S. "'Pele's Tears' and Their Bearing on the Origin of Australites," *Bull. Geol. Soc. Amer.*, XXVII (1916), 51–55.

Australites are thought to be of volcanic origin since bodies of distinctly volcanic origin show that similar forms can originate in the atmosphere from rotating liquid bodies.

MOORE, RAYMOND C. "The Relation of the Buried Granite in Kansas to Oil Production, *Bull. Amer. Assoc. Petroleum Geol.*, IV (1920), 255–61.

This paper is petrographically of interest from the short description of a buried ridge of granite extending as an elongated mass from north of the Nebraska state line into Kay County, Oklahoma. The ridge reaches its highest elevation near the north boundary line of Kansas in Nemaha County, where it is less than 500 feet below the surface. It descends gradually to the south and forms a saddle in northwestern Wabaunsee County, then rises in Morris and Chase counties in underground peaks of different elevations.

O'HARRA, CLEOPHAS C. "A Bibliography of the Geology and Mining Interests of the Black Hills Region," *South Dakota School of Mines Bull.*, XI, 1917. Pp. 216–17, map 1.

A very important and useful bibliography of the Black Hills, containing not only titles and references, but abstracts of each of the 1,187 items listed.

OSANN, A. "Der chemische Faktor in einer natürlichen Klassifikation der Eruptivgesteine, I." *Abhandl. d. Heidelberger Akad. d. Wiss., Math.-naturw. Kl.*, Abh. 8, 1919. Pp. 126, pls. 5.

This is another important contribution to the chemical classification of rocks, and one which will be welcomed by everyone who uses Osann's system. In former publications the determination of the s, A, C, F, a, c, and f values, and their plotting in triangular diagrams ended the attempt at classification. Here regular pigeonholes are established, so that it is a very simple matter to locate analyses of similar rocks. The first 23 pages of this work are devoted principally to general discussions and various modifications of the previous methods of calculation. It is to be regretted that nowhere is there given a definite set of revised rules for the computation of the formulae. The various modifications here proposed can be adopted by those already familar with the system, but a beginner will find it necessary to follow the discussion through many pages of print to obtain for himself a workable set of rules. It is true that the system has gradually developed, and various changes have been introduced, but it would seem that it is now in such form that well-defined rules could be given, and it is to be hoped that in the near future Professor Osann

will publish such a set. From page 23 to the end various type rocks are calculated and the relations between their mineral composition and their position in the classification are discussed. The general divisions of the new groups are as follows:

	c=0–0.5	c=1–2	c=3–4	c=5–6	etc., etc.	c=13–14
a=30 –28						
a=27 –25						
a=24 –22						
etc., etc.						
a= 9 – 7						
a= 6 – 5						
a= 4 – 3						
a= 2 – 1						
a= 0.5– 0						

The values of *a* have intervals of 3 between 30 and 7, from 6 to 1 the interval is 2: the values of *c*, except the first, have intervals of 2.

The limiting values of the older rock types are:

Rock Type	Limiting Values			
	s	*a*	*k*	Percentage SiO_2
Granite and Quartz-diorite	82.5–69	26–27	1.8 –1.2	63
Syenite and Diorite	74 –57	24–23	1.1 –0.9	65–51
Essexite and Gabbro	60 –47	12– 0	0.9 –0.7	53–46
Mafic Essexite and Gabbro, Hornblendite and Pyroxenite	46 –42	2– 0	0.7 –0.6	44–42
Dunite, Peridotite, and basic Hornblendite	41 –36	2– 0	0.6.–0.5	40–35
Nephelite-syenite	67 –63	26–13	0.8 –0.7	59–54
Theralite and Shonkinite	53 –49	12– 5	0.65–0.5	46–43
Alkalic feldspar-free Rocks	58 –46	26– 3	0.86–0.39	50–39
Anorthosite	65 –50	11– 1.5	1.0 –0.9	57–44

The first three groups included the acid, neutral, and basic igneous rocks. According to Rosenbusch, the acid have 65 per cent, the neutral between 64 and 52 per cent, and the basic below 52 per cent of SiO_2. The fourth and fifth groups, with their extrusives are mafic, basic, and ultra basic differentiates of the third group. The sixth group is an alkalic side-group of the second, the seventh of the third. The eighth group includes rocks of very different mineralogical character and can be regarded only as a basic side-group of the sixth and seventh. The last group is connected with the second and third but belongs to the alkali series.

OSANN, A. "Der chemische Faktor in einer natürlichen Klassifikation der Eruptivgesteine, II," *Abhandl. d. Heidelberger Akad. d. Wiss., Math.-naturw. Kl.*, Abh. 9, 1920. Pp. 59.

In the first part, reviewed above, the plutonic rocks are discussed; in this the extrusives are considered. One hundred and fifty-one types, based on 973 analyses, are given, but owing to present conditions of publication, only the type rocks are shown, and the number of analyses falling in each group is indicated. The tabulation follows that given for the plutonites.

PATTON, HORACE B. "Geology and Ore Deposits of the Platoro-Summitville Mining District, Colorado," *Bull. 13. Colo. Geol. Surv.*, 1917. Pp. 122, maps 3, pls. 40.

The region here described lies between Creede, Alamosa, Chama, and Pagosa Springs. The rocks which occur are very similar to those described in the folios of the San Juan region. Short descriptions are given of rhyolite, latite (two chemical analyses), andesite (one analysis), basalt, monzonite (one analysis), quartz-monzonite-porphyry and diorite.

PETROGRAPHIC COMMITTEE. "Report on British Petrographic Nomenclature," *Mineralog. Mag.*, XIX (1921), 137-47.

A committee, consisting of Watts, Elsden, Flett, Teall, Thomas, Tyrrell, Evans, Hatch, Holmes, Prior, Rastall, and Smith, from the Geological Society of London and the Mineralogical Society, report on ninety rock-names and petrographic terms which have been used in more than one sense by British authors, and make recommendations as to those which are to be rejected and definitions of those to be retained. Some of the recommendations are in direct opposition to the recommendations by the Committee on Petrographic Terms of the U.S.G.S. in 1897 and 1898. For example the British committee recommend the use of the terms porphyry and porphyrite in the sense used in Germany, namely porphyry for rocks with dominant alkali-feldspar and porphyrite with dominant plagioclase. The U.S.G.S. recommended that "Porphyry and its derivatives are to be used as purely textural terms, without limitation to mineralogical groups. Porphyry will thus apply to all rocks, whatever their composition, containing phenocrysts in a distinct groundmass, and without regard to the size of the grains of the groundmass. Porphyrite is discarded as superfluous. . . . ." Further in regard to the use of the hyphen, the U.S.G.S. recommends that only similar terms be hyphenated, thus two mineral terms or two rock terms, as biotite-muscovite granite, granite-syenite, etc., but mineral and rock, or rock and texture, as unlike terms, are not united. The British committee say: "When a mineral-name, or names,

and a rock-name are compounded to form a name of 'specific' signification, these should be joined by a hyphen; e.g. biotite-granite." With the usage of porphyry in the sense of the U.S.G.S., porphyritic rocks are defined as granite porphyry, diorite porphyry, etc., but the British committee says, "The name granite-porphyry is ambiguous, and should not be used." Why ambiguous is not clear, unless it is thought possible that it may be confused with porphyritic granite. But porphyritic granite and granite prophyry are quite different things. It is recommended that adamellite be discarded, or only used for acid members of the monzonite series, and monzonite is to be restricted to rocks of the type occurring in the Monzoni district. If monzonite is used in the original sense of de Lapparent for the Monzoni rocks, it is a collective name and embraces monzonites Brögger, gabbros, and pyroxenites. Personally the reviewer would like to see the intermediate rocks, monzonite and adamellite, dropped (see *Jour. Geol.*, XXVII [1919], 38, and XXVIII [1920], 229), and the term granodiorite returned to its original sense (*Jour. Geol.*, XXVII [1919] 168). The latter recommendation is also made by the British committee. The usage of the term panidiomorphic by the British committee (following Rosenbusch) as given in the definition of aplite, is regarded by the reviewer as incorrect. A panidiomorphic rock would be one in which all of the constituents have their own crystal boundaries. Such a rock is almost inconceivable: and the texture of aplite is as far removed from this as it can possibly be, for it has a saccharoidal texture, that is, one in which all of the constituents are xenomorphic (allotriomorphic); it is, consequently, panxenomorphic or panallotriomorphic. The British committee recommend the terms allotriomorphic and idiomorphic in preference to xenomorphic and automorphic. The latter, however, have priority by one year. The term essexite "is retained for rocks practically identical with, or which show but slight divergence from, the original type of Salem Neck, Essex Co., Massachusetts," which is a large order since the original locality shows such a divergence of type. It is recommended that diabase be dropped and dolerite used. One is as bad as the other. Diorite and gabbro are given the meanings accepted in the United States (namely separated on the basis of the feldspar), and Harker's usage is not followed. Leuco- as a prefix for leucite, as used by Lacroix, is put in the discard. The less exact terms basic, intermediate, and acid are used in preference to subsilicic, mediosilicic, and persilicic of Clarke.

POWERS, SIDNEY. *A Lava Tube at Kilauea.* Private Publication. Pp. 7, pls. 5.

Describes a lava tube, extending from the Kaluaiki pit crater in a northeasterly direction for 1,494 feet with a drop of 73 feet. The maximum height is 20 feet, the maximum width 22 feet. In the roof of the tube there are more than a dozen small, conical cupolas "blow-piped" by gas escaping from the lava. These cupolas vary from 1 to 8 feet in height and with similar basal diameters. Thirty-three cross-sections, drawn to scale, are given.

POWERS, SIDNEY. "Volcanic Domes in the Pacific," *Amer. Jour. Sci.*, XLII (1916), 261–74, figs. 5.

Gives data on various volcanic domes, showing size, composition, and important features. Viscosity is the principal factor which determines whether the magma shall appear as a flow or dome. In some cases a flow comes first, then a dome; in others the dome comes first and the lava later breaks through the crust.

POWERS, SIDNEY. "Granite in Kansas," *Amer. Jour. Sci.*, XLIV (1917), 146–50.

An earlier report on the granite ridge mentioned above (Moore, Ramond C., *Bull. Amer. Asso. Petro. Geol.*, IV, 1920).

QUENSEL, PERCY. "De kristallina Sevebergarternas geologiska och petrografiska ställning inom Kebnekaiseområdet," *Geol. Fören. Förhandl.*, XLI (1919), 19–52, figs. 15, pls. 2, profile 1.

Describes the crystalline schists from Kebnekaise, in Lapland. An analysis of a feldspar-rich "gneiss-mica-schist" is given.

QUENSEL, PERCY. "Zur Kenntnis der Mylonitbildung, erläutert an Material aus dem Kebnekaisegebiet," *Bull. Geol. Inst. Upsala*, XV (1916), 91–116, pls. 4.

The mylonites from Kebnakaise are regarded as primarily derived from igneous rocks, though some sediments may occur among them.

QUENSEL, PERCY. "Über ein Vorkommen von Rhombenporphyren in dem präkambrischen Grundgebirge des Kebnekaisegebietes," *Bull. Geol. Inst. Upsala*, XVI (1918), 1–14, pl. 1.

Describes a rhombic porphyry in which the feldspar is a microcline antiperthite ($Or_1Ab_9An_2$). It is microperthitic and zonal, with a central portion of plagioclase surrounded by pink potash feldspar or white albite. The change from center outward is not gradual, but abrupt, and seems to indicate a sudden change in the chemical character of the magma.

QUIRKE, TERENCE T. "Espanola District, Ontario," *Mem.* 102, *Canadian Geol. Surv.*, 1917. Pp. 92, map 1, pls. 6, figs. 8.

The Espanola district is 43 miles west of Sudbury, and comprises an area of 116 square miles. The rock formations are principally Huronian, with older metamorphosed sedimentary schists and slates, and intrusive greenstones and granite. The Huronian rocks are cut by diabase dikes and sills, more or less

contemporaneous with the faulting of the region. Pleistocene formations lie directly upon the Pre-Cambrian, and consist of fluvioglacial deposits, till, clays, and lake sands.

QUIRKE, TERENCE T., and FINKELSTEIN, LEO. "Measurements of the Radioactivity of Meteorites," *Amer. Jour. Sci.*, XLIV (1917), 237–42.

Gives the radium content of twenty-two meteorites not previously determined. It is found that the average stony meteorite is considerably less radioactive than the average igneous rock, probably less than one-fourth that of an average granite, and that the metallic meteorites are almost free from radioactivity.

REINHEIMER, SIEGFRIED. *Der Diorit vom Buch bei Lindenfels im Odenwald mit einem Anhang über einige mikroskopische Methoden.* Inaug. Dissert., Heidelberg, 1920. Pp. 63, Figs. 8, Photo. Pl. 3.

Two "diorites" and a gabbro are described. No modal percentages are given, but in general it may be said that the main rock from the Buch consists of more amphibole than plagioclase with accessory biotite and a little quartz. The plagioclase is zonal with cores $Ab_{12}An_{88}$ and outer zones Ab_{40-46} An_{60-54}. There is a pale to colorless amphibole and one that is green, the latter usually surrounding the former. The author says a "gabbro tendency" is shown, and that diallage is proxied by an amphibole of similar chemical composition. The second rock, from Kreuzer's quarry, near Winterkasten, is similar, although generally the amphibole and plagioclase are in equal amounts. The feldspar is approximately $Ab_{17}An_{83}$, biotite is rare, and quartz is wanting. The third rock from near Laudenau differs from the other two. It is described as a gabbro of the type of the Scandinavian hyperites. The dark minerals consist of green amphibole poikilitically intergrown with plagioclase, and diallage and olivine. The plagioclase is Ab_9An_{91}. Since the plagioclase in all of the rocks is labradorite to bytownite, the reviewer would call all the rocks gabbro (amphibole gabbro) in spite of the statement of the author that the magma must have been poor in lime. (No chemical analyses are given.)

Associated with these rocks are certain diaschistic rocks, among them diorite-pegmatite, schlieren of "needle-diorite," and beerbachite.

In the Appendix the determination of refractive indices in cleavage fragments of amphibole by the immersion method, and the determination of 2V with the Federow stage are discussed.

RICHARDS, H. C. "The Building Stones of Queensland," *Proc. Roy. Soc. Queensland*, XXX (1918), 97–157, pls. 3, figs. 10.

The physical, chemical, and mineralogical characters of various available building stones, with their good and bad qualities, and a list of structures with the stones used, are given.

RICHARDS, H. C. "The Volcanic Rocks of Springsure, Central Queensland," *Proc. Roc. Soc. Queensland*, XXX (1918), 179–98, pl. 1, figs. 6.

The oldest rocks of this area are Paleozoic sediments, consisting of sandstones, gravels, and shales, and some limestone. The volcanic rocks, with a total thickness of 1,000 feet, are divided into three groups: a Lower Series which consists of basaltic agglomerate and basaltic flows, followed by trachyte tuffs and flows, then a return to basaltic flows. The Middle Volcanic Series consists of trachytic tuffs and flows which are "really phonolite in the strict petrological sense." In the weathered material, precious opal has been obtained. The Upper Volcanic Series consists of basaltic flows to a thickness of 600 feet. Three new chemical analyses are given. The upper and lower basalts are similar and closely comparable with the composition of the average basalt of the world. Richards says: "The basaltic rocks. . . . may represent outpourings of a comparatively undifferentiated primary basaltic magma. . . . . Gravitative differentiation may have gone on to some extent as the lower series is olivine free, while the upper series is rich in olivine (fayalite). . . . The intruded terrane almost certainly contains limestone, and the solution of this material to a small extent would be regarded by Daly as sufficient to result in the production of the phonolitic material from the calcic basic magma. . . . . The writer, however, in dealing with the origin of the volcanic rocks of south-eastern Queensland, regarded them as being differentiates of a single original magma."

RICHARDSON, W. ALFRED. "The Marginal Features of a Basic Dyke at Peldar Tor, Charnwood Forest," *Geol. Mag.*, LVIII (1921), 170–77.

A much altered greenstone (dolerite) dike which intrudes dacite shows a chilled marginal phase and a crystalline center. At the contact the margins are laminated, resembling columnar basalt, but actually consist of alternating sheets of country rock and dike. Three possible explanations for the lamination are given.

RICHARDSON, W. ALFRED. "A Method of Constructing Rock-Analysis Diagrams on a Statistical Basis," *Mineralog. Mag.*, XIX (1921), 130–36.

Diagrams for plotting the chemical analysis of a rock are given.

RICHARDSON, W. ALFRED. "A New Model Rotating-Stage Petrological Microscope." *Mineralog. Mag.*, XIX (1920), 96–98.

Describes a new Swift petrographic microscope.

RICHARZ, STEPHAN. "Die Basalte der Oberpfalz," *Zeitschr. d. deutsch. geol. Gesell.*, LXXII (1920), 1–100. Pl. 2, Figs. 8.

The basalts of the Oberpfalz are very similar megascopically, but under the miscroscope three types are recognized; pure nephelite-basalts, pure feldspar-basalts, and nephelite-bearing feldspar-basalts. No melilite-basalts were found although they occur at Steinberg near Hohenberg in Oberfranken. Some of the basalts are rich in both endogenic and exogenic inclusions, others rarely contain any. Among the inclusions are olivinefels, pyroxenites, fritted sandstones, and basalt-jaspis. In addition to the usual minerals, labradorite, nephelite, augite, olivine, magnetite, some glass, there occurs in some of these rocks, biotite. In the inclusions aegirite, katophorite, sanidine, oligoclase-andesine, quartz, and the recrystallization minerals, natrolite, phillipsite, calcite, aragonite, opal, and a new mineral called magnalite, occur. Field observations show that the basalt occurs in the form of dikes much more commonly than previously thought. The width varies from 50 to 200 meters.

RINNE, F. *Gesteinskunde.* Leipzig, 1921. 6th and 7th (double) ed., 8vo. Pp. 365, Figs. 510.

It is almost impossible in a short review to do justice to a general textbook which does not aim to present any startling new theories. One can do little more than give a summary of the table of contents. The first 120 pages of this book, which is not only a petrography but a petrology, are devoted to general geological modes of occurrence of igneous rocks, sediments, and crystalline schists, jointing, parting, and other structures, petrographic methods, and the mineral constituents of the rocks. The final 235 pages are devoted to descriptive petrography of igneous, metamorphic, and sedimentary rocks. As an introduction to the igneous rocks there are thirty-eight pages devoted to their chemical composition and modes of expressing these graphically, differentiation, gases in magmas, sequence of crystallization with many diagrams, and textures and structures. Following the general descriptions of the igneous rocks are a few pages on meteorites. Introducing the sedimentaries are sections on origin, weathering, transportation, deposition,

and diagenesis. Among the descriptions of the sediments, that on salt deposits is especially detailed, occupying sixteen pages. The crystalline schists are preceded by chapters on origin and textures. The book is profusely illustrated with photographs, undoubtedly excellent in the originals, but not well reproduced. The book may well serve as a text for students who have a sufficient command of German.

ROSENBUSCH-WÜLFING. *Mikroskopische Physiographie der Mineralien und Gesteine. Bd. I. Die petrographisch wichtigen Mineralien. Pt. I. Untersuchungsmethoden.* 5th ed., Stuttgart, 1921. Pp. 252, Figs. 192, and a colored plate.

This well-known work again has been revised, enlarged, and practically rewritten by Wülfing, so that it bears very little resemblance to the third edition of Rosenbusch. The present instalment of the book, which is the first half of the first part, all so far published, deals with methods of preparation, and with general theories of optics. Much new material has been added, and some of the old has been omitted to keep the size of the book within reasonable bounds, but how much has been omitted it is impossible to determine, in many cases, on account of the rearrangement and the appearance of only the first part as yet.

Following the Introduction, which is somewhat condensed, there is a section on preparation methods. The history of microscopical research, the description of stereographic projection, and the graphical methods and formulas, which followed in the fourth edition, are entirely omitted. Thirty-five pages on the preparation of thin sections come next, instead of being inserted between the chapters on optical principles and optical instruments, a decided improvement in arrangement. Here are given a number of new devices for cutting, grinding, and polishing. The cutting of oriented sections is described in considerable detail, occupying with the instructions for cutting plane surfaces and polishing, some fifteen pages.

Optical methods are introduced by a general discussion of theories of light. In the preceding edition, following the discussion of the indicatrices, the Fresnel ellipsoid, and uniaxial and biaxial ray and wave surfaces, came a section on lenses, microscopes, and various accessories. In the present edition this is omitted, probably to come later, and the discussion of optical phenomena continues unbroken. The same arrangement holds throughout the book. All of the theoretical material is brought together and the determinative methods are omitted, undoubtedly to be collected in the second half. This makes the different

parts of the book much more unified and gives a better appearance, but will it be so easy for the student?

After a discussion of interference phenomena there is a new section on the dispersion of birefringence and the departure of the interference colors of crystals from the pure colors of Newton's scale. Section 46, on the movement of light, has been entirely rewritten, and the figures have been redrawn. The material in this portion of the work has been so radically rearranged that it is difficult to compare it with the old edition, especially since some of the material may have been transferred to the future second part.

In the preceding edition, following the theoretical discussion of the intensity of transmitted light, came a chapter on the practical methods of determining extinction angles. In the new edition this is omitted, apparently to be given later, and the theoretical part is followed by an explanation of the phenomena in convergent light, and there are given the formulas for isochromatic curves, isogyres, and so on. The steps in obtaining Neumann's formula for calculating the values of birefringence in any section have been increased from a half to four pages, a very considerable help to the student who cannot refer to the original article. The section on interference figures also has been much extended, the explanation of the cross and rings obtained in uniaxial crystals alone having been increased from four and one-half to nine and one-half pages. Becke's skiodromes are given in illustration of both uniaxial and biaxial figures. Under dispersion the old cuts have been discarded and new and much better drawings, as well as photographs showing dispersion, have been inserted. The subject of pleochroism has been extended from twelve to sixteen pages, and a new section of two pages on luminescence has been added.

Polarizing prisms, which formerly came before the discussion of microscopes, and before the discussion of interference, pleochroism, etc., now comes near the end of the first half and takes up twenty-one pages. Finally, there is the concluding section on Monochromatic Light, increased from six to fourteen pages. Here are now given liquid color filters, more material on monochromatic flames and the monochromator, and a new description of the mercury lamp.

The book is now, as it has always been in the past, the one big indispensable work which begins where others end. Author and publisher are to be congratulated on its appearance. Press work, paper, and illustrations are excellent and, in spite of the difficulty of obtaining good paper, are fully up to the standard of previous editions.

SCHEURING, GEORG. "Die mineralogische Zusammensetzung der deutsch-südwest-afrikanischen Diamantsande," *Beiträge z. Geol. Erforsch. d. Deutschen Schutzgebiete*, Hf. I, 1914. Pp. 49, map 1, fig. 1.

Describes the minerals associated with the diamond in German Southwest Africa. Of petrographic interest from the description of a separating apparatus which might possibly be applied to the preliminary separation of rock constituents.

SCHLOSSMACHER, K. "Zur Erklärung der Becke'schen Linie," *Centralbl. f. Min. Geol.*, etc. (1914), 75-79, figs. 2.

A theoretical discussion of the Becke line. The writer shows that with vertical contacts the phenomenon is to be explained by Snell's law; with inclined contacts between minerals the effects are more complex, and may be accounted for in part by the explanation given by Grabham.

REVIEWS

The Problem of the St. Peter Sandstone. By CHARLES LAURENCE DAKE. Bulletin of School of Mines and Metallurgy, University of Missouri, Vol. 6, No. 1. Rolla, 1921. Pp. 228, pls. 30.

Professor Dake finds the St. Peter sandstone in Minnesota and Wisconsin equivalent to the upper part of the Chazy, and in Oklahoma and Arkansas, to all of it. It is unconformable with the Potsdam sandstone in Wisconsin, and with strata above the Potsdam farther south, up to the Arbuckle limestone in Oklahoma.

A study of the characteristics of the sandstone, such as composition, texture, and structural features was undertaken with a view to determining the origin of the sand. The author appears to have started with hospitable attitude toward the hypothesis that the sand is of eolian origin, but in the end he was led to the conclusion that several of the criteria usually held to indicate an eolian origin for sand (1) are "of less positive significance than is generally believed"; that (2) they are "significant only of conditions of transportation, and not of deposition"; that (3) they are "sometimes inherited from an older formation"; and that (4) they are "not present in the St. Peter in any appreciably greater perfection than in other sandstones of the same region known to be marine." He also holds that structural features imposed on a formation at the time it is laid down are "the only positive criteria as to conditions of deposition. These criteria point rather definitely to the marine origin of the [St. Peter] formation."

Of special significance in this connection is the basal conglomerate present in many places, for in it there is "no sign of wind polish or of faceted forms, and nothing comparable to desert varnish" (p. 187).

This conclusion as to the origin of the St. Peter sandstone is not only interesting in itself, but seems to suggest that the "continental deposition" idea, long neglected, has of late been overworked. In sundry recent publications it has almost seemed that if a marine origin for a formation is not proved, a non-marine origin is assumed. This volume is a wholesome check to this tendency.

Some of the author's detailed conclusions are as follows:

1. The composition and texture of a sandstone may furnish criteria regarding its derivation and transportation, but not regarding its method of deposition.

2. The history of the sand grains of a sandstone is usually so complex, including transportation successively by winds, streams, and waves, that textural criteria afford no proof whatever of the nature of transportation, even to the *last deposit in which the sand is found*. . . . .

3. The structural and stratigraphic relationships in the field, including such features as the character of bedding, cross-bedding, unconformities, lateral gradation and similar associated phenomena, constitute the only valid criteria for determining the conditions under which a deposit was last laid down, and these may sometimes give a clue to the method of transportation *to that particular resting place.*

4. The purity of the St. Peter sandstone, while very remarkable, as compared with that of average sandstones, is . . . . not sufficiently different from that of associated marine sandstones to demand any essentially different explanation of origin; . . . .

5. Size of train, *in pure quartz sands*, in general, is limited by the size of quartz grains in average igneous rocks, and is not a satisfactory criterion of wind-blown sands.

6. The size and uniformity of grain in the St. Peter is so near that of the Roubidoux marine sand, that no discriminations as to origin can be made on such a basis.

7. The degree of rounding and frosting of grains, which has been used as one of the chief arguments for eolian origin of the St. Peter, may often be masked by secondary quartz enlargement, but making due allowance for such modification, the St. Peter cannot be distinguished, on this basis, from the marine Roubidoux, or from older Cambrian sandstones. . . . .

8. The St. Peter shows bedding better developed than cross-bedding, and does not show typically developed dune-structure, even in the protected basal layers in the valleys of the old erosion surface. . . . .

11. Limestone layers occur at many horizons, particularly at the south, but are known as far north as north central Iowa and northern Illinois, and indicate marine deposition.

12. Oscillation ripple-marks in sand layers, marine fossils in limestone beds . . . . occur in Arkansas and Missouri, next above the unconformity [at the base of the series], showing submergence before the advance of the sand into the region.

13. Marine fossils are found in the St. Peter as far north as Minneapolis, not only in the uppermost transition layers, but also at three horizons, more than 60 feet below the top. These would not appear to have resulted from working over of dune deposits.

14–19. The St. Peter appears to have been derived from a relatively low land mass to the northward. This land is believed to have sloped southward, in which direction its rivers flowed, to have been affected by a moderately humid climate, but not to have been clothed with vegetation, because land plants had not yet developed. The land included pre-Cambrian crystalline rocks and a broad fringe of Potsdam sandstone.

20. The derivation of the St. Peter, largely from this Potsdam belt in which the sands were already well assorted and rounded, together with the added sorting and rounding by wind work in the supply area, and by waves in the sea, explains in a wholly satisfactory manner the high degree of purity and rounding of its grains.

21. These sands were delivered to the sea both by rivers and to a minor degree directly by winds, and were distributed chiefly by waves and currents.

22. The shores of this sea were fluctuating, but during middle and late St. Peter time, were for the most part north of the Iowa-Minnesota line.

23. North of that line there is quite probably a small amount of St. Peter that is truly unmodified terrestrial deposit. . . .

24. South of the Iowa-Minnesota line, conditions of both transportation and deposition were almost wholly marine, and in this area there did not exist during any part of St. Peter time, a great interior desert of drifting sand.

A discussion of the geographic conditions under which this and other early Proterozoic formations were made, closes the volume.

R. D. S.

Deposits of Manganese Ore in Arizona. By E. L. Jones, Jr., and F. L. Ransome. Bulletin 710-D, United States Geological Survey, Government Printing Office, Washington, D.C., 1920. Pp. 92, pls. 6, figs. 8.

The production of manganese ore as such in Arizona dates from 1915. The producing district lies in the more southern part of the state. The greater part of the ore worked bears at least 35 per cent manganese, and not more than 4 per cent iron. The ore is shipped east to Illinois, Alabama, Tennessee, and Pennsylvania, and lately also to California. Perhaps the chief difficulty encountered in production lies in the inaccessibility of the mines to railroads, which necessitates "packing" the manganese out of the mining district, a tedious and expensive process.

Various scattered manganese have been studied by Mr. Jones in the preparation of this paper. Dr. Ransome describes those at Bisbee and Tombstone. In the latter district, the sequence extends from the pre-Cambrian Pinal schist through Cambrian, Devonian, Mississippian,

Pennsylvanian, Triassic (or Jurassic), and Comanchean rocks. These are mostly limestones, though the early Mesozoic is marked by porphyritic intrusions and the lower part of the Cambrian series is quartzitic. The manganese ore, largely psilomelane, occurs in irregular bodies in close association with fissures in the Carboniferous limestones; the deposits follow the fissures, or extend laterally from them along certain beds of limestone; they seldom descend to depths greater than fifty feet and are worked by open cuts or shallow inclines. With the hard psilomelane are lesser amounts of barite, quartz, a green copper-arsenic compound (new species), and soft black pyrolusite; chalcolite is occasional.

In the Tombstone district the manganese grades into ores rich in the precious metals; it occurs in irregular pipelike masses or chimneys distributed along fault zones.

Almost certainly these manganese deposits are related to the copper ores, as they are generally closely associated. The manganese ores are unquestionably supergene, being generally found only in the oxidized zone. Psilomelane deposition seems to have been conditioned chiefly by fissuring. In the Tombstone district, manganese-silver ores are as common as manganese-copper ores in the Bisbee region, and possibly the manganese zone here represents a leached silver zone. The deposits, on account of their irregularity, can only be worked under unusual conditions. Possibly not more than 60,000 tons of 40 per cent ore are available in these two districts combined.

Elsewhere in the state, in Coconino, Graham, Greenlee, Maricopa, Mohave, Pinal, Santa Cruz, Yavapai, and Yuma counties, there are smaller manganese deposits. Here veins, brecciated zones, bedded deposits, and irregular deposits with travertine, all furnish greater or lesser amounts of manganese ores. The ores are in pre-Cambrian granites and gneisses, Tertiary rhyolites, andesites, and dacites, and Quaternary basalts, as well as in limestones and quartzites of Paleozoic age, sandstones of Tertiary age and course clastics of the Quaternary. The manganiferous silver veins occupy an important place among the vein deposits; they are well shown in the Hartshell shear zone ores and in the Globe district; in such cases the manganese oxides are psilomelane, pyrolusite, braunite, manganite, and wad. There may be more or less iron oxide associated, as in the Globe district, where the ores are intimate mixtures of manganese- and iron-oxides. Where braunite is the chief ore mineral, it is commonly associated with cerusite, vanadinite, and wulfenite.

Veins barren of silver are widely scattered throughout the southern part of the state and include most of the deposits examined. They are most common in Tertiary lavas. The ore-shoots vary greatly in size. The ore consists of oxides derived from the weathering of vein material, hence its depth depends largely on the permeability of the rock to circulating water. The ore minerals are psilomelane, pyrolusite, and manganite; these are accompanied by barite, calcite, and iron oxide.

Bedded deposits vary as to character and associated rocks. They may be contained in tuffs, or they may be the result of replacement of sandstone. They are generally of Tertiary age. Such deposits do not extend to great depths and are worked through shallow pits and shafts. The manganese minerals are psilomelane, pyrolusite, manganite, and subordinately braunite. Quartz, feldspar, iron ores, and calcite are the chief gangue minerals—partly secondary, partly the unreplaced minerals of the rock. Much of this ore, developed in sandstones and only partially replacing the country rock, is siliceous.

Manganese ore associated with travertine is known from one locality only; here the travertine and the clayey manganese-bearing beds are capped by basalt. The manganese mineral is principally botryoidal and vesicular psilomelane.

A detailed description of the geography, geology, and manganese deposits of each of the districts is given; for these the reader is referred directly to the carefully prepared paper itself.

C. H. B., Jr.

World Atlas of Commercial Geology; Part I, Distribution of Mineral Production. United States Geological Survey, 1921. Pp. 72, pls. 72.

The purpose of this atlas, prepared by more than a score of geologists, is "to set forth graphically and to describe concisely the basic facts concerning both the present and the future sources of the useful minerals." Part I deals chiefly with present sources; later parts will exhibit, so far as practicable, the mineral reserves of the world. The maps of Part I, which deal with the most important thirty mineral commodities, are arranged in groups of eight, each group containing (1) a map of the world showing production and, for major commodities, consumption by countries in 1913, the last year of normal production; (2) a map of each of the continents, indicating production by countries, districts, or fields, in percentages of the world's production in 1913; and (3) a map of the United States, exhibiting production in 1918 by states, districts, or fields, in percentages of the total output of the country.

The accompanying text presents briefly and effectively fundamental facts concerning the various minerals, under headings such as uses, geologic occurrence, geographic distribution, technology, centers of consumption, and the like.

The atlas is an outgrowth of investigations of mineral problems begun during the war, investigations of a type too long delayed in this country, for the facts concerning the distribution, quality and quantity, availability, and commercial and political control of the world's mineral resources are destined to affect increasingly our trade and industries and our relations with other peoples.

HARLAN H. BARROWS

An Introduction to Paleontology. By A. MORLEY DAVIES. London: Thos. Murby & Co.; New York: D. Van Nostrand & Co.

Mr. Davies has planned his book with the intention of making it, above all else, a practical, usable textbook for courses in the elements of paleontology. To this end, he begins with those animals which are most common as fossils, and which can be studied most easily by the beginner—the Brachiopoda. He first describes certain common species, in order to give the student a clear idea of the general characters of the group, and then presents a brief, but tolerably adequate, account of the entire class.

From the Brachiopoda the author carries his text along the ascending scale, through the vertebrates. He then returns, begins with the Echinodermata, and follows the descending order, finishing with the Protozoa. The system of treatment violates tradition, and certainly has the disadvantage of leaving a beginning student in something of a muddle as regards classification. But it has the advantage of beginning with the easy, and proceeding to the difficult, and parallels the system of treatment used in several of the more recent and progressive high-school texts in zoölogy.

On the other hand, Mr. Davies has adopted a few innovations that are neither advantageous nor, so far as can be seen, justifiable. There is no clear ground for separating the Molluscoidea into two groups, and putting the Bryozoa with the corals; neither is it plain why the Pythonomorpha have been omitted entirely, and the Aves reduced to an order among the Reptilia. These are points that an instructor may correct, but it is not clear why he should be forced to do so.

C. L. F.

The Mineral Resources of the Philippine Islands for the Years 1917 and 1918. Contributors: ELMER D. MERRILL, VICTORIANO ELICANO, LEOPOLDO A. FAUSTINO, W. H. OVERBECK, and T. DAR JUAN. Issued by the Division of Mines, Bureau of Science, Bureau of Printing, Government of the Philippine Islands, Manila, 1920. Pp. 75, pls. 8, tables 12, and analyses.

This issue of *Mineral Resources of the Philippine Islands* deals with the years 1917–18, following the plan expressed in the first issue of 1908, which was continued by annual publications until 1916. Of great interest in the publication under review is the increase in the importance of coal, the slump in gold mining, the appearance of asbestos as a mineral product of the Islands, and the discovery of more deposits of iron. Lesser resources treated are sulphur, manganese, and asphalt. The gold production in 1917 was about 1,990,000 grams; in 1918 it was about 50,000 units less. Silver production increased from 81,000 odd fine grams in 1917 to 128,000-odd in 1918. A still greater advance is recorded in the coal production—from 5,000 tons (round numbers) in 1917, to 15,000 tons in 1918. Since the year 1907 there has been a steady increase in mineral yield except in 1910.

In spite of the increasing gold production of the Islands, it must be admitted that gold mining is still in the formative stage. The largest production comes from Masbate and the Mountain Provinces, and the largest single mine is the Benguet Consolidated Mining Company, in the Mountain Province district.

Three sources of iron ore have been exploited in the islands, and magnetite sand, briquetted, is also being experimented with. Lead and zinc deposits in Marinduque Island are described. They are fissure veins, 4 to 10 feet wide, running as high as 60 per cent lead or 45 per cent zinc; the minerals are galena and sphalerite, the gangue is quarts, and the country rock andesite. Manganese has been produced to some slight extent, and copper is mined in Mancayan.

Most Philippine coal is really lignite, but good bituminous coal is known from Polillo Island and in the Zamboango district. At the close of 1918 twenty-three mines were producing coal. In the better mines a modified room and pillar method is used, the room being also an entry. Considerable waste, especially on the part of small operators, is the rule. Mine gases are rare, the walls are good, and ventilation problems in these shallow mines are simple; transportation, however, is a real difficulty in coal mining. An interesting feature of coal production is the development of producer gas plants on the Islands.

Asbestos manufacture is a new industry in the Philippines. At present only one district—that of Ilocos Norte—is productive. Both amphibole and chrysotile asbestos are known. An asbestos plant is now operating in Manila.

Oil exploration is so far merely preliminary and confined to the Lake Lanao-Cotabato district (Mindanao) and to the Tayabas field. The Mindanao oils have a specific gravity of .93 to .91 as analyzed; the base is paraffin.

Sulphur is found in solfataras and in the impure state, mixed with volcanic ash, in several localities. The production of cement has virtually ceased because of the failure of the largest cement plant. Fire-clay, lime, sand and gravel, stone, salt, and mineral and artesian waters are the other resources treated. A separate chapter is devoted to glass-making; this demonstrates the accessibility of all the material necessary to the process—lime, silica, and alkali.

The report urges the revision of the federal mining laws and the establishment of a school of mines. The adoption of a leasehold system is advocated; present mining law in the Philippines requires that 200 pesos worth of development be performed annually on located, unpatented claims, which "does not always accomplish the purpose sought either by the Government or the claim holder."

The report contains a directory of mine-owners, lessees, and operators, and a transcript of the mining laws of the Philippine Islands. Several good photographs accompany the report, but unfortunately others are carelessly mounted—possibly the error of the publisher—and still others show little or nothing of the very features they are presumed to illustrate. Some of these shortcomings may no doubt be laid at the door of the smallness of the funds available, which has compelled a reduced staff to disperse its energies over a large field. Similarly, no doubt, the general lack of detailed geological descriptions may be accounted for. All in all, the report is of distinct value.

C. H. B., Jr.

Deposits of Manganese Ore in Costa Rica and Panama. By Julian D. Sears. Bulletin 710-C, United States Geological Survey, Government Printing Office, Washington, D.C., 1919. Pp. 31, pls. 1, figs. 28.

This bulletin is actually two separate papers—one dealing with the manganese of Costa Rica, the other with that of Panama.

The known manganese deposits of Costa Rica are all in the Province of Guanacaste, on the Pacific Coast. They are widespread, but generally

either of low grade or of small extent. Only two really important deposits are worked.

The important manganese deposits of Costa Rica are in the Nicoya Peninsula, which is very hilly, with a "backbone" running in a generally northwesterly direction. The east coast (Nicoya Gulf) is low, with swamps and estuaries, while the Pacific coast is high and rugged. The rocks are chiefly sandstone, shale, conglomerate, and limestone. Most of the sediments have undergone considerable dynamo-metamorphism, the greater part being now iron-pigmented quartzite, but other less highly colored quartzite occurs higher in the sequence. Silicified limestone, shale, and breccia are also reported. Igneous rocks include basic fine-grained types, largely flows (?). Some intrusions are also thought to characterize the region though no plutonic rocks are actually described. Structurally the area seems to indicate an igneous basement, with superjacent sediments that have been intricately folded and faulted since deposition.

The ore-bodies are manganese oxides, partly soft (pyrolusite?), partly hard and crystalline. Iron oxide is generally low, but silica occurs mechanically admixed. The oxides are found in pockets or troughs between the red metamorphosed rocks and lighter colored sediments, or may be in direct contact with igneous rock. Generally the deposits are too small to merit another term than "pocket," but they may be as large as 500 by 100 feet, averaging 5 feet in thickness. The exact size of these ore-bodies is not determinable, and estimates of a reserve based on a 40–45 per cent ore are therefore not dependable.

The ores are related to fault zones but not all the faults of the region are ore-bearing. The ore is attributed by the writer to hydrothermal action, the hot, ascending solutions passing along the faults and spreading on planes of contact between formations and depositing the manganese as a carbonate or silicate which was later oxidized. The great silicification of the wall rock and close relation between the ore and fissures are supposed to lend credence to this view. On the other hand the manganese may be the product of downward concentration, deposited because of the impermeability of the highly metamorphosed rocks.

A detailed discussion of the mines and prospects emphasizes their economic insignificance. Two only are of importance as producers at present, those at Playa Real and at Curiol, and one prospect (Pavones) may prove to be productive in the future.

In Panama two manganese deposits are known on the west side of the Boqueron River, about 20 miles east of Colon. The country near

the mines is hilly, and in places reaches altitudes of 1,000 feet. The rock immediately adjacent to the deposits is fine-grained sediment containing much siliceous cement, or hard, gray, siliceous limestone. Associated with the ore-bodies are shales and breccias, and a dark igneous rock, probably basalt.

At Mine No. 1, the manganese occurs as mixed oxides, largely in bowlders, or segregated in lenses and sheets in varicolored clays. The manganese ore may be in stringers or beds in the clay. It appears to be the result of concentration and segregation. Taking all the possible sources of manganese together, about 10,000 tons are available at this locality.

At Mine No. 2 the ore is also in bowlders, which lie on the surface, or in clay banks; here too are sheets of manganese ore, ranging in thickness to 15 feet. Manganese is also segregated in a zone in bedded breccia, formed apparently through concentration in the residual clays that weathered from the breccia.

In general, therefore, the manganese ores appear to be residual, not unlike those of the Piedmont district of southeastern United States.

C. H. B., Jr.

The Iron and Associated Industries of Lorraine, the Sarre District, Luxemburg, and Belgium. By Alfred H. Brooks and Morris F. LaCroix. United States Geological Survey, Bulletin 703, 1920. Government Printing Office, Washington, D.C. Pp. 131, pls. 2, figs. 12, and numerous tables, including statistics on Belgian iron and coal production.

This report was prepared at Paris for the use of the American Commission to Negotiate Peace. It illustrates again the value of geology in fields normally considered foreign to the science. It calls to mind too the desirability of making peace-terms on the basis of such carefully organized facts with a view to stabilizing world-industry, rather than on the principle that to the victor belong the spoils.

The purpose of the original report was to lay before the commission certain facts relating to the pre-war use of Lorraine iron ore and thereby to forecast the probable future of the metallurgical industry in Lorraine as modified by the new national control which were under discussion when the report was submitted. . . . . The original report was in effect an argument for the adoption of certain policies with reference to the iron and coal industries of central Europe. . . . . For these reasons the reader will find that certain parts of the report are presented as arguments rather than as expositions.

The importance of the iron ores of Lorraine Annexee and French Lorraine may be shown by the fact that they furnished in 1913 34 per cent of the total iron consumed in Europe.

Lorraine Annexee, that part which Germany controlled subsequent to 1872, produced in 1913 75 per cent of the entire German output of iron ore. The reserves aggregated about 1,830,000,000 tons of ore averaging about 30 per cent iron. More than two-thirds of the coke used in Lorraine Annexee came from the Westphalian and Aix-la-Chapelle districts; the remainder, only some 1,500,000 tons, was from the nearby Sarre field. The European iron reserves in other fields were being rapidly depleted, and it would thus have been greatly to the interest of Germany to obtain control also of the French Lorraine field. German capital already owned 10 to 15 per cent of the entire iron district by purchase before the outbreak of the war, and if French Lorraine had been annexed, Germany would have controlled 50 per cent of Europe's iron resources. As it is, however, "the Treaty of Versailles has left Germany with only 7 per cent of Europe's iron reserves, while France owns 48 per cent. Moreover, the deposits of iron ore in the German Republic are widely scattered, and some of them are not favorably located for economic development. Therefore any large production of iron and steel in Germany must be based on imported ores." Only her Westphalian coking coals prevent the immediate annihilation of Germany's metallurgical industry; this coal, it is shown in the report, is necessary to assure the economic utilization of France's Lorraine ores.

In general the iron deposits of Lorraine occur in a belt extending northward from Metz along the pre-war frontier between France and Germany in an area averaging 60 kilometers long and 20 kilometers wide. The more southerly Nancy iron district lies entirely within the pre-war French territory and forms an outlier of the main field. The dip of the beds is gently westward, though modified by slight folds and faults.

The ores are mined at a low cost; this, taken with their great extent, their proximity to coal fields and markets, and their composition, which adapts them to the basic process, gives them their great value. The phosphorus content is 1.5 to 2 per cent, fairly constant, and yields valuable slag fertilizer. The iron mines in the occupied parts of Lorraine were but little damaged by the Germans, but the furnaces, which might later be expected to compete with German ones, were injured or destroyed.

About 74 per cent of all coking coal that is sufficiently near for economic use in Lorraine lies in the Westphalian fields of Germany.

The Sarre fields can only contribute some 22 per cent of the needed coal, so that with the restoration of Lorraine Annexee, France holds much smaller coal reserves than either Germany or Great Britain.

In the Westphalian field of Germany the coal is close to tidewater and is connected by rail and by waterways with the iron and steel centers of Lorraine and Belgium. The district produces about half of the total German output of pig iron, and in 1913 some 45 millions of tons of Lorraine ore were smelted there. About 180 coal mines are operated. The Sarre coals lie near the Lorraine field—some thirty kilometers east—but are far inferior in coking qualities to those of Westphalia. There are from 27 to 32 workable seams, aggregating about 40 meters in thickness. The total reserve, estimated to a depth of 2000 meters, is about 16 million tons. The coal cokes but poorly, yielding on the average 50 per cent coke; in blast furnace practice, therefore, it is customary to make the charge of equal quantities of Sarre and Westphalian fuel. The Sarre coal is really best used for steam, gas, and domestic purposes.

There are no large coal reserves in Belgium, excepting possibly in the Campine Basin. The Campine coals, after development has proceeded a little further, may, with the Sarre, supply enough coal for all the Lorraine ores; but in an open market, they could not compete successfully with the higher grade Westphalian coal.

Luxemburg bears reserves of iron that should last about thirty-five years. It supports large furnaces; there were in 1913, forty-six blast furnaces and six steel plants. Of the six large corporations that control most of the stock, four are German, one Belgian, and one mixed capital.

The entire compilation is to be commended, first for its purpose —the application of economic facts to international problems—and second for its accuracy and completeness. Two good maps illustrate the geographic relations of the coal and iron districts in question; many graphs, tables, and diagrams make the salient points doubly clear.

C. H. B., Jr.

The Earlier Mesozoic Floras of New Zealand. By E. A. Newell Arber, M.A., Sc.D., F.G.S., F.L.S. Wellington: New Zealand Geological Survey, Palaeontological Bulletin No. 6, 1917. Pp. 72, pls. 14.

This memoir is concerned with an account of the earlier Mesozoic floras of New Zealand, with which very little work has hitherto been attempted. A majority of the species described are new. One result

of the work has been to show that, despite assertions to the contrary, no trace of any Paleozoic flora has been found in these islands. Rumors of the presence of Glossopteris-bearing rocks have no foundation in the material studied. Even in Permo-Carboniferous times, when the southern continent of Gondwanaland included a large part of the Southern Hemisphere, New Zealand did not, on the basis of the known evidence, form any part of that continent. Whether beds of Permo-Carboniferous age do or do not occur, is not definitely known.

So far as may be concluded from present evidence, the Mesozoic land connections between Antarctica and the temperate regions of the Southern Hemisphere appear to have been chiefly in the direction of New Zealand and Australia. Although somewhat similar Wealden floras are known in South America, the evidence is too meager to warrant conclusions concerning its connection with other southern lands.

The portion of the paper devoted to systematic paleobotany includes the description of forty-eight species, all of which are figured. The report includes an extensive bibliography.

A. C. McF.

ERRATA

Journal of Geology, Vol. XXX, p. 269, footnote, line 2, "Oct., 1922" should read "*Sept.*, 1922."

P. 269, footnote, line 8, "pp. 36" should read "*Vol.* 36."

P. 286, footnote 1, should read "Cf. footnote 3 on page 270."

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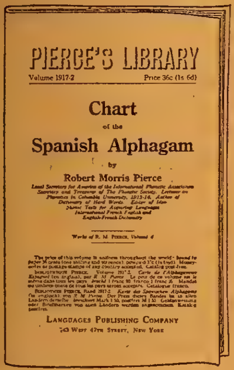

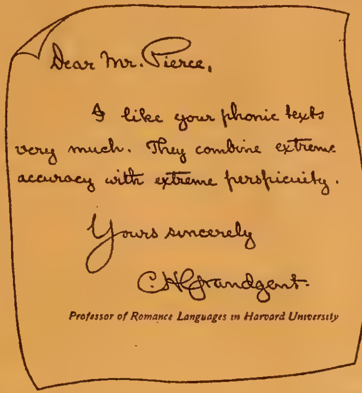

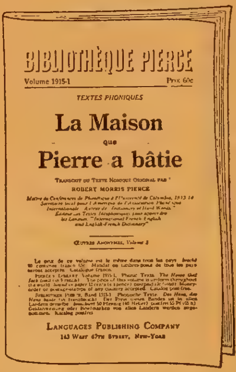

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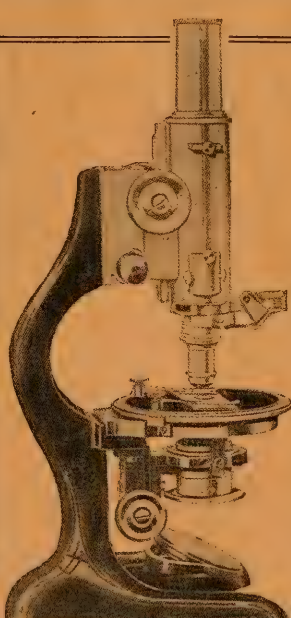

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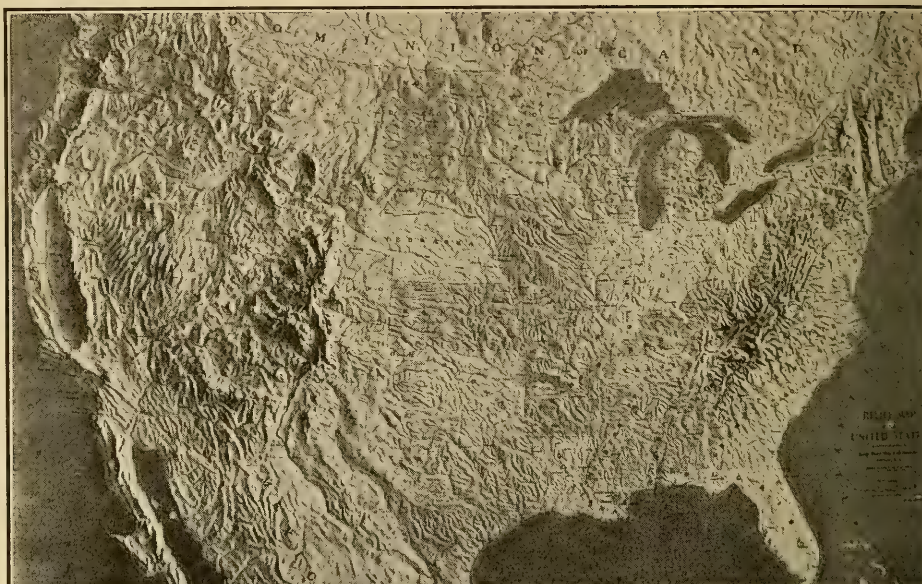
Among articles to appear in early numbers of the *Journal of Geology* are the following:

The Lava Field of the Paraná Basin, South America. By CHARLES LAWRENCE BAKER.

The Problems of the Anorthosites and Other Monomineral Igneous Rocks. By F. LOEWINSON-LESSING.

The Cycle of Erosion and the Summit Level of the Alps. By W. M. DAVIS.

Some New Features in the Physiography and Geology of Greenland. By LAUGE KOCH.



VOLUME XXX NUMBER 8

THE JOURNAL OF GEOLOGY

November-December 1922

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

J. H. L. VOGT
Trondhjem, Norway

VI

THE INFLUENCE OF THE LIGHT VOLATILE COMPOUNDS (H_2O, CO_2, ETC.)

The physico-chemistry of the light volatile compounds in the magmas has lately been explained in two treatises published at the same time and independently of each other, namely:

P. Niggli. Die leichtflüchtigen Bestandteile im Magma. Preisschrift von der Fürstlich Jablonowkischen Gesellschaft zu Leipzig, 1920.

Th. Vogt. Lecture in the Society of Science, Kristiania Meeting, April 16, 1920.

Referring to these two treatises and to H. E. Boeke's "Grundlagen der physikalisch-chemischen Petrographie" (1915, especially pp. 256–63), we will begin with a general orientation.

We will discuss a binary system at constant pressure, in which we think of a very high pressure, between A and B, with melting point, respectively critical temperature, S_A, K_A and S_B, K_B where S_B lies notably higher than K_A (illustrated by Fig. 52). The "critical curve" cuts the curve of the gas phase. In this system, when

applied to the combination H_2O:silicate, the water at a low temperature will only keep dissolved a trifle of silicate. The eutectic point (E in Fig. 52) of the water solution will consequently practically coincide with S_A which is illustrated by the schematic Fig. 53, copied from Th. Vogt's treatise where, under the signature B, we keep together the different silicate components, for instance, in a granite.

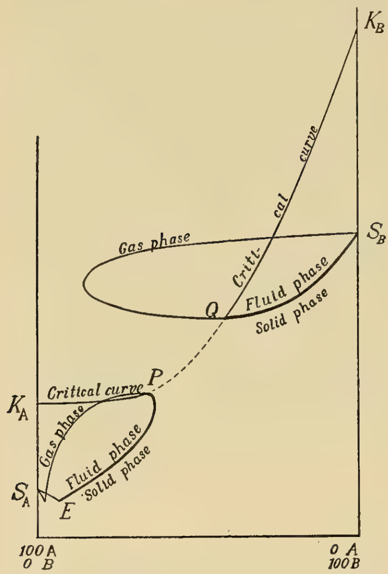


FIG. 52.—The quantitative proportion between A and B as abscisse and the temperature as ordinate.

We may here distinguish between three temperature stages:

1. From S_B (the melting point of the silicate) to Q.

We here get a crystallization of the silicate by continuously decreasing temperature, the quantity of H_2O increasing in the mother liquid (the rest-magma). There is at last produced a magma relatively strongly enriched in H_2O, of the composition Q.

At the same time some of the light volatile compounds escape, so we get a gas phase which can effect pneumatolytic formations. Concerning this we refer to the explanation on the fundamentals given by Th. Vogt and Niggli in Beyschlag-Krusch-J. H. L. Vogt, *Erzlagerstätten*, II, second edition (1921), pp. 555–61.

The gas pressure (the pressure of the escaping gas phase) at S_B (thus for pure B) is very little and increases with the quantity of the light volatile compounds dissolved in the magmatic solution (up to Q). The gases escape when the gas pressure exceeds the external pressure. At a relatively low external pressure, as for the crystallization of a magma at a little depth, the light volatile compounds will consequently escape at higher temperatures, thus also at a relatively earlier stage than at higher pressure, by the

solidification of the magma in a depth, for instance, of 5 or 10 kilometers. And in the last case the escaping gas must dissolve in itself more of the silicate compounds. Th. Vogt applies this to very instructive geological examples.

2. At the temperature interval Q–P there exists a gas (H_2O in supercritical condition with some dissolved silicate in gas-formed condition) from which more or less silicate may crystallize directly from the gas.

3. From P (the critical point of H_2O containing some B in solution, which point lies somewhat higher than the critical point, $K_A = 374°$, of pure H_2O) to E (Fig. 52) or S_A (in Fig. 53, where E and S_A practically fall together) we get a liquid very rich in H_2O, which may effect divers hydrotermal formations. Further on we get a gas phase consisting of quite predominant H_2O and only a very little B.

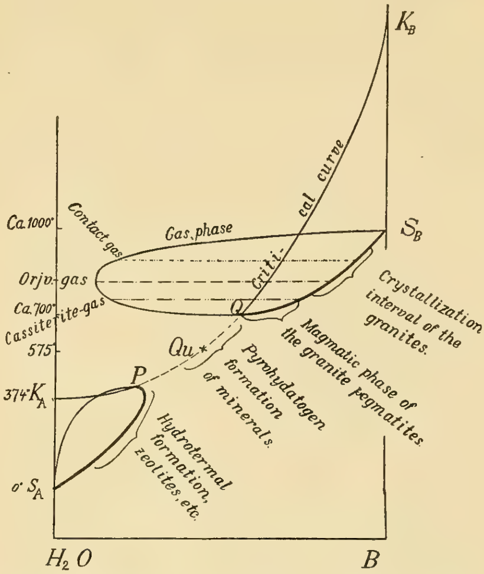


FIG. 53.—System A:B, where A = H_2O and B = silicate (silicates of the granite). Qu = quartz point (inversion points between α and β quartz, at one atmosphere at 575° and at pressure somewhat higher).

The pressure may be indicated by axes perpendicular to the plane of the paper. At relatively low pressure in the deep-seated magmas and consequently at high temperature, contact gas escapes, giving as a result the contact metamorphic ore deposits of the Kristiania type. At higher pressure and consequently at a somewhat lower temperature, contact gases escape with a higher solution of silicates, etc., giving, as a result, contact metamorphism of the Orijårvi type ("Orjv. gas"). After Th. Vogt.

By far-advanced crystallization of the granite magma escape "cassiterite gases" (Sn F_4, etc.), giving as a result the minerals of the cassiterite deposits.

We shall in the following pages only treat the *crystallization* in a magma, containing light volatile compounds, and not employ

ourselves with the pneumatolytic, pyrohydatogen, and hydrotermal processes effected by the escaping gas.

During the crystallization of the magma the light volatile compounds will conduct themselves in different ways:

1. Some will, if the gas pressure is sufficiently high, escape from the magma.

2. Some will be inclosed in the crystallizing minerals as gas- or liquid-inclusions (for instance, the well-known pores in quartz, at low temperature chiefly consisting of liquid CO_2).

3. Some may enter in solid solution into the crystallizing minerals. The quantity calculated by weight—or molecular weight—of these "occluded" gases is, however, very little.[1]

4. Some may, under certain circumstances, enter into the crystallizing minerals, for instance H_2O in muscovite, biotite or hornblende, CO_2 in calcspar, etc.

5. The rest of the gas will remain in dissolved condition in the magma and be concentrated in the mother-liquid, by continuously decreasing temperature until it reaches Q.

These light volatile compounds dissolved in the magma exist in the reciprocal solution in the same manner as the other solution-components. If we think of a magma containing mix-crystal components, as Ab and An besides dissolved water, the water will not influence the mix-crystal system. And if we have a ternary system of two components independent of each other, *a* and *b* and also a little water (in lesser amount than that equivalent to Q on Figs. 52–53), the sequence of the crystallization will be between *a* and *b*, dependent on the quantitative relation between *a* and *b* in relation to a eutectic boundary curve, beginning at the binary eutectic E_{a-b}. The further extension of the curve will be stipulated by the third component, H_2O, present in small amount. With a slight quantity of H_2O the relation between *a* and *b* on the boundary curve will be almost exactly the same as in the binary eutectic E_{a-b}. That is to say, the sequence of the crystallization between

[1] By heating to below the melting point of the rocks these occluded gases may escape and thereby break the rock into pieces. In this manner many rocks (granite, syenite, gabbro, etc.) may be completely desintegrated by fire.

a and *b* will be displaced only very inconsiderably by the presence of some dissolved water.[1]

We have here supposed that H_2O enters as an independent component (H_2O). But it may also be thought that H_2O, CO_2, HCl, etc., under certain conditions, partly also may form special combinations (for instance H_2SiO_3, H_4SiO_4, H Al SiO_4, etc.), which may be broken up during the run of the crystallization. Hereby there is a possibility for complications which will be very difficult to explore.

In a binary system (under high pressure) of a light volatile component, as, for instance, H_2O, and a silicate, as Ab, An, Or, Ca Mg Si_2O_4, etc., even a little H_2O will effect a relatively considerable depression of the melting point of the silicate, and this depression is nearly proportional to the quantity of H_2O, etc. We refer to the explanation given by Niggli (1920), pages 34–35, and illustrated by his Figure 2, II and III. And in general, the light volatile components (H_2O, CO_2, HCl, etc.) will effect a tolerably considerable depression of the crystallization interval.

From theoretical reasons it must be presupposed that the light volatile components may effect a very considerable increase of the *thin-fluidity*. This is, as far as I know, not verified by laboratory experiments, but that it is the case, may *inter alia* be proved by the fact that the magma of granite-pegmatite dikes, in spite of the low crystallization interval (about 800°–700°) must have been extremely thin-fluid.

With regard to the quantity of the light volatile components in the various eruptive magmas, we may present the following general consideration.

By crystallization-differentiation in a parent-magma with a certain percentage of light volatile components (as, for instance, H_2O), the first separated crystals will, in most cases because of their increased density, sink into a deeper-lying and higher-heated magma-layer where they are dissolved (or resorbed). As we shall

[1] In this connection we will cite a portion of the conclusion in the treatise of P. Niggli, "Die Gase im Magma" (*Centralbl. f. Min.*, etc. [1912], pp. 337–38). "Es ergiebt sich aus den (physikalisch-chemischen) Versuchen dass in vielen Fällen (hoher Druck) die Gasmineralisatoren wie eine andere Komponente behandelt werden können, dass also Vogt's Ansicht, dass einfache Schmelzflüsse schon viele petrographische Probleme erleuchtern, richtig ist."

see in a later paper, there results from this process, as a rule, after repeated crystallization-differentiations, the *anchi-monomineral magmas* (for example, anorthosite, dunite), where the original quantity of the light volatile compounds in the parent-magma must be considerably diluted.

By the segregation of the anchi-monomineral magmas, the light volatile components, so far as they do not escape, will remain in the rest-magma. Extensive crystallization-differentiation results in *anchi-eutectic magmas* (most gabbros, norites, syenites, granites) and as the *final* product of the differentiation running in the anchi-eutectic direction are brought out the *granitic* magmas.

Consequently, we must a priori presume that the light volatile components on an average will be in the smallest quantity in the anchi-monomineral magmas which must have been "dry" or "almost dry melts." A somewhat higher percentage may generally occur in the anchi-eutectic magmas and indeed especially in the granitic magmas. And in the last ones result, as the final solution at a very great depth (after Th. Vogt) where the light volatile components cannot, or can only in part, escape the granite pegmatitic magmas where we may expect a relatively extensive concentration of the volatile components.

As support to this theoretical deduction we shall first point out that *miarolitic druses*, according to my own field observations, generally are completely lacking in anorthosites, dunites and petrographically related rocks. On the other hand, they are very common in many granites, quartz-syenites, etc., and in the miarolitic druses we often find, as well known, a supply of pneumatolytic minerals proving that these druses must have been genetically connected with the volatile components.

Further, according to my own field observations, tourmaline and other pneumatolytic minerals are completely or almost completely wanting in the Norwegian massives of anorthosite and also in the numerous but certainly, as a rule, very small massives of peridotite. By far the most *magmatic-epigenetic* (pneumatolytic, pyrohydatogen, and hydrotermal) ore deposits are connected with acid or intermediate igneous rocks (granite, quartz monzonites, etc.). These ore deposits are, in relation to the extension of the

igneous rocks, relatively much rarer with basic igneous rocks, and they are, so far as I know, entirely lacking in the often very large massives of anorthosite. As more fully treated in Beyschlag-Krusch-Vogt (*Die Erzlagerstätten*, Vol. II, 2d ed. [1921], pp. 564–65), this may be explained by the relatively high content of volatile compounds in the granitic magmas. And as far as the granite-pegmatite dikes are concerned, these are, as is known, frequently characterized by a very considerable supply of pneumatolytic (or magmatic-pneumatolytic) minerals.

We further get very instructive information in investigating the relations between *orthorhombic* and *monoclinic pyroxene* on the one hand, and *hornblende, biotite* and *muscovite* on the other, in the various rocks.

As is known, muscovite is noted by Tschermak with the formula $KH_2Al_3(SiO_4)_3$ and biotite (meroxene) with $K_2HAl_3(SiO)_4 \cdot nMg_2SiO_4$, where n is 3 or at times somewhat lower. Some of K usually is replaced by Na, and especially in biotite some of Al by $\dddot{Fe}$ and some Mg by $\ddot{Fe}$. Further some F commonly enters into the mica, replacing O (or HO ?). The relation between K and H moreover, is subject to certain variations. These standard formulas prove that the muscovite contains considerably more H_2O[1] than the biotite. Primary muscovite from granite-pegmatite dikes (and granite) contains, according to the analyses at hand, mostly 5–8 per cent H_2O and 11–9 per cent K_2O+Na_2O, and the biotite from granite and other acid igneous rock, mostly 1–2 à 2.5 per cent H_2O and 9–7 per cent K_2O+Na_2O.

Also the hornblende commonly carries some H_2O (or HO), viz., in the igneous rocks at most 2 per cent, usually considerably less, and tremolite up to 2.5 per cent.

As to the conditions for the formation of biotite in the igneous rocks, we refer especially to the account given by N. L. Bowen[2] and to the treatise of P. Niggli,[3] "Die gasförmigen Mineralisationen im Magma."

In the previously (pp. 430–35) described orbicular quartz-norite from Romsaas, consisting of *ca.* 63 per cent hypersthene, 8 per cent biotite, 24 per cent plagioclase (on an average $Ab_{42}Or_3An_{55}$), 4 per

[1] Here and in the following I do not enter upon the question on whether it is hydroxyl, HO, or H_2O, which appears.

[2] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. of Geol.* (1915).

[3] *Geol. Rundschau*, III (1912).

cent quartz, and a little rutile and apatite, the individualization began with the crystallization of hypersthene in large quantities. Then followed, during a short stage, a simultaneous crystallization of hypersthene and biotite, while the Mg, Fe-silicate present in the magma during the last stage entered totally into the biotite.

The *anhydrous meta*-silicate *hypersthene* thus during the later stage of the crystallization—even after the percentage of SiO_2 in the residual magma was quite considerably increased, viz., to about 61 per cent—was replaced by the *hydrous ortho*-silicate *biotite*. This must be due to the fact that the original percentage of H_2O of the magma was so small, that at first hypersthene could be formed. But when a considerable quantity of this mineral was segregated H_2O became so strongly concentrated that biotite also could be formed. And during the last stage, when the remaining mass was reduced to *ca.* $\frac{3}{10}$ of the entire rock, the quantity of H_2O was thus very considerably increased, so that the formation of hypersthene ceased, and biotite was formed instead.

As we shall treat more particularly in a later paper, there occur, in the quartz-norite massive at Romsaas, a number of pegmatitic "Schlieren" and dikes of nearly the same mineral composition as the intervening mass between the orbs of the orbicular norites, but with the plagioclase ($Ab_{68}An_{32}$) somewhat richer in Ab and with somewhat more quartz. These pegmatitic "Schlieren," etc., must represent the end-magma, resulting from a very late stage where the quantity of H_2O was still more concentrated. This is in accordance with the pegmatitic structure and moreover with the fact that the Mg, Fe-silicate here only enters into biotite, while hypersthene is entirely lacking.

In several norites from Norwegian localities examined by me, biotite is entirely lacking in almost all thin sections from one single field (Ertelien on Ringerike) while a little biotite occurs in most fields, mostly 2, 3, 4, or 5 per cent, and only as a rare exception, as in the quartz-norite from Romsaas, as much as 8 per cent. Where both hypersthene and biotite occur, the last one always, as just described from Romsaas, belongs to a somewhat later stage than the hypersthene. It is especially to be emphasized that neither the absolute quantity of biotite nor the quantitative proportion

between biotite and hypersthene stands in any relation to the composition of the rocks determined by the quantitative chemical analysis. The formation of biotite thus is not dependent on the content of K_2O in the rocks nor on the proportion of K_2O to MgO (or MgO+FeO). In some norites with 0.5–0.7 per cent K_2O the entire quantity of K_2O enters into the feldspar (as $KAlSi_3O_8$ in the plagioclase). In other norites with the same percentage of K_2O, as much as *ca.* $\frac{6}{7}$ of the content of K_2O of the rock may enter into the biotite and only $\frac{1}{7}$ into $KAlSi_3O_8$ of the plagioclase. When we consider this in the light of all the other observations here treated, the conclusion clearly is justified that the cause of the greatly varying quantity of biotite in these rocks must be due to the variations in the quantity of H_2O in the magma. But even in those norites that carry as much as *ca.* $\frac{1}{6}$ of biotite in proportion to the sum of hypersthene and biotite, the H_2O percentage in the magma must have been rather small.

As earlier mentioned, many Norwegian norites and gabbros do not contain any primary hornblende at all, and where this mineral occurs it is somewhat younger than the pyroxene (p. 521). We may here apply the same considerations as those regarding the relation between the hypersthene and biotite in the quartz norite from Romsaas.

The anorthosites constantly carry, as is well known, a small admixture of hypersthene, or sometimes of augite (diallage) and olivine, while primary hornblende seems to be entirely lacking.

As we shall show in a later paper, the peridotite series in the first stage of concentration—carrying about 35–50 per cent olivine and with a chemical composition 41–49 per cent SiO_2, 5–10 Al_2O_3, 6–10 CaO, 0.25–2 alkalies, 10–15 FeO, and 15–25 MgO, thus about 0.75 MgO:0.25 FeO—in almost every case is characterized by some primary hornblende, at times also by some primary biotite. In the progressive concentration of the olivine—and simultaneously with diminishing percentage of Al_2O_3, CaO and alkalies and increasing Mg_2SiO_4 in proportion to Fe_2SiO_4—the hornblende is, on an average, diminishing in quantity and in peridotite rocks with at least 85–90 per cent olivine hornblende as a primary formation is entirely or almost entirely lacking.

The formation of the minerals in both the anorthosites and the olivine rocks—with at least, respectively, *ca.* 90 per cent plagioclase (labradorite-bytownite) and 85–90 per cent olivine (poor in iron)—thus indicates a crystallization of a magma very poor in H_2O.

As to the relation between *hypersthene, biotite,* and *biotite+muscovite* in the *alcali granites,* we shall as a beginning cite a very instructive statement by H. Rosenbusch (*Mikroskop. Phys. d. Massigen Gesteine,* II, 1 [1907], p. 71): "Die Analyse eines Hypersthengranites und eines gewöhnlichen normalen Alkaligranite sind nicht sicher zu unterschieden."

In granites with composition

73–77	per cent	SiO_2
11–15	"	Al_2O_3
1.5–3	"	Fe_2O_3+FeO
0.2–0.7	"	MgO
0.25–1.4	"	CaO
5–8	"	$K_2O+Na_2O_4$

(with varying proportion of K_2O and Na_2O) we find, in some cases, though rather rarely, hypersthene—in by far the most cases biotite—and at times biotite+muscovite.

In the hypersthene-granite from Birkrem and environs in the Ekersund Soggendal-field, the hypersthene (opt. neg.), according to my determination, shows axial angle *ca.* 70°, the composition is thus *ca.* 0.64 $MgSiO_4$:0.36 $FeSiO_4$ (equivalent to about 23 per cent MgO and 18 per cent FeO). The quantity of hypersthene in this rock (with *ca.* 73–75 per cent SiO_2) according to microscopical examination is quite small, about 1 per cent, corresponding to *ca.* 0.2–0.25 per cent MgO+0.2 per cent FeO. An analysis published by C. F. Kolderup[1] shows 73.47 per cent SiO_2, 0.12 TiO_2, 15.42 Al_2O_3, 1.02 Fe_2O_3 (including FeO), 0.20 MgO, 1.35 CaO, 5.57 Na_2O and 3.64 K_2O, thus stoechiometric 0.70 Na_2O:0.30 K_2O. The three analyses of charnockite (hypersthene-granite) from Madras[2] (India) with 75.3–77.5 per cent SiO_2, on the other hand show in part a middle

[1] Das Labradorfelsgebiet bei Ekersund und Soggendal, *Bergens Museums Aarbog* (1896), p. 96.

[2] Cited from H. S. Washington, *Chemical Analyses of Igneous Rocks,* 1884–1913 (1917, pp. 88 and 956).

proportion of Na_2O to Ka_2O, and in part predominantly K_2O, viz., almost 0.7 K_2O:0.3 Na_2O. We shall group the contents of MgO and K_2O in the just-mentioned analyses of hypersthene-granite with 73.5–77.5 per cent SiO_2:

per cent MgO....	0.20	0.43	0.69	0.60
" K_2O....	3.64	4.14	3.34	6.13

It appears from this that the formation of hypersthene in these alkali-granites is not dependent on any especially high percentage of MgO (or MgO+FeO) nor on an especially low percentage of K_2O.

According to my examinations of some Norwegian "white granites," relatively rich in acid plagioclase (according to the nomenclature of V. M. Goldschmidt[1] "Trondhjemite") from the north of Norway carrying both *muscovite* and *biotite*, the muscovite occurs exactly in the same way as the biotite. Especially it is to be emphasized that the muscovite-individuals frequently are congested in small aggregates—they thus show "together swimming structure" (synneusis structure) indicating formation at a very early stage—and they are in more places deposited on the small apatite-crystals which serve as "Fixkörper." Some individuals show idiomorphous contours parallel to 001, as well as perpendicular to 001, against the quartz and the feldspar. Most frequently occur the usual lobed outlines, however, as in most of the individuals of biotite in granite.

In some of these muscovite-bearing granites, as, for instance, in a rock from Narvik—with twice as much muscovite, in leaves up to 3 mm. in size, as biotite—we observe crystallographically parallel growths, at times in alternating strata of the two mica-minerals, as described by Rosenbusch (*op. cit.*, p. 57).

In other samples, however, as in a rock from Fustervand near Mosjöen, with nearly twice as much biotite as muscovite—the last one in leaves only *ca.* 1 mm. in size—we observe individuals of muscovite with idiomorphic contours inclosed in the biotite, indicating that the muscovite at least for a great part was formed at an earlier stage than the biotite.

[1] "Geologisch-petrographische Studien im Hochgebirge des Südlichen Norwegens," *Ges. d. Wiss.*, Kristiania (1916).

Rosenbusch (*op. cit.*, p. 51) maintains the view that the formation of muscovite in the granite must be explained as a pneumatolytic process[1] "worauf auch seine weite Verbreitung in den Pegmatiten deutet." This may perhaps to a certain extent be adequate for the muscovite, which belongs to miarolitic druses, but it cannot be applied to the common muscovite evenly distributed in the granite. The structure proves that the muscovite has crystallized from the magma at a very early stage, in part at the same time and in part somewhat earlier than the biotite.

Whether hypersthene, biotite, or biotite and muscovite shall crystallize in acid granites with *ca.* 75 per cent SiO_2 does not depend upon the presence in the magma of those compounds that are shown by the quantitative chemical analysis, nor upon certain variations with regard to pressure, time of cooling, etc. When to this are added the facts that muscovite as a primary formation in igneous rocks is limited to granite-pegmatite dikes and to some granites, and that muscovite is characterized by relatively much H_2O, biotite by a smaller percentage of H_2O, and hypersthene by no H_2O at all, we must conclude that the decisive factor is the varying content in the magma of H_2O (eventually also other volatile compounds).

In the two-mica-granites examined by me, there is up to about twice as much muscovite as biotite. If we turn to the granite-pegmatite dikes, however, we find at times, though very rarely, as in the case of some districts of Smaalenene in Norway, muscovite only, without any biotite at all, and the quantity of muscovite may here rise to as much as about 10 per cent.

The great majority of alkali-granites are characterized by biotite. Two-mica-granites, in Norway as elsewhere in the world, are rare, and hypersthene-granites, so far as yet known, are still more rare.

The content of H_2O in the granite-magma thus in most cases must have been lying within the interval that gives biotite. As a

[1] While H_2O dissolved in the magma appears in the same manner as the other components, I do not find it natural or right to extend the meaning of the term pneumatolysis to include the formations of minerals, as biotite or muscovite where the magmatic dissolved H_2O was co-operant.

rare exception only, the quantity of H_2O may have been so small, that hypersthene has been formed (or, principally in somewhat more basic granites, a monoclinic pyroxene, besides or instead of hypersthene), and relatively seldom only the content of H_2O, etc., was somewhat higher, so that muscovite was formed together with biotite. In granite-pegmatite dikes of analogous chemical composition the content of H_2O, etc., throughout must have been considerably higher, as we here never find hypersthene or diopside, but mica and not seldom muscovite together with biotite, occasionally even muscovite alone without biotite.

And if we further draw a parallel between the granites (with *ca.* 75 per cent SiO_2) on the one hand and norites, gabbros, anorthosites, etc. (with *ca.* 50 per cent SiO_2), on the other, we will find that mica plays a predominant part in the first-mentioned acid rocks, while in the last-mentioned basic rocks biotite is much more subordinate than the pyroxenes, and muscovite is entirely lacking.

By three different methods of investigation, viz., in the study of the distribution of miarolitic druses, in the study of the magmatic-epigenetic formations of ore deposits, etc., connected with igneous rocks, and in the study of the relation between mica (biotite, eventually also muscovite), and in part also hornblende, and pyroxene, we thus get a confirmation of the theoretically drawn conclusion that the granites on an average contain the highest percentage of H_2O, etc.

Then we come to the question of how much H_2O, etc., there may have been present at the start of the crystallization in the magma and especially in the granite-magma.

In the muscovite granite-pegmatite dikes there may occur about 10 per cent muscovite containing 5–8 per cent H_2O. In proportion to the entire magma there thus entered into the *early* crystallizing mica *ca.* 0.5–0.8 per cent H_2O. But still there must have been present so much H_2O that the later separated minerals might also obtain the pegmatitic structure. This quantity of H_2O (with CO_2, etc.) escaped, except those small quantities that entered into the microscopic pores or was occluded in the separating minerals. This, including the content of H_2O in the mica, will only make 1 per cent by weight of the entire magma. The gas that escaped in the

course of the crystallization, at least in part, will have formed miarolitic druses. These play a rather subordinate part in regard to the quantity in the granite-pegmatite dikes, however.

Even in the granite-magma the quantity of H_2O will hardly have amounted to much more than a few per cent. And the crystallization of the igneous rocks must, as pointed out by many earlier investigators, among them also myself, be conditioned by the decreasing temperature of the magma and not by the diminution of volume occasioned by the escaping H_2O, etc.

According to Clarke's well-known calculation the earth's crust consists to a depth of 10 miles (= *ca.* 16 km.) at a medium density of the rocks of 2.7, of

93.39	per cent	solid crust,	with 2.02 per cent H_2O
6.58	"	"	ocean, with *ca.* 97 per cent H_2O
0.03	"	"	atmosphere

If we were to presume that the entire quantity of water of the ocean was supplied from the igneous magmas, and assume a medium thickness from the solid crust of three times 10 miles = *ca.* 48 (or 50) km., we would get a quantity of H_2O:

$$\tfrac{1}{3}\times 6.58\times 0.97+97.81\times 2.02=4.06 \text{ per cent } H_2O.$$

This value, *ca.* 4 per cent, must indicate the maximum original content of H_2O in the initial parent-magmas. But of this again a considerable part must have escaped before the parent-magmas could have been cooled so far that crystallization-differentiation began. The various partial magmas, resulting from magmatic differentiation, which, crystallized to form the igneous rocks, must thus, on an average, have contained less, very likely quite considerably less, than 4 per cent H_2O.

In concluding, I wish to note that I have learned much from P. Niggli's great work: "Die leichtflüchtigen Bestandteile im Magma" (1920), but I cannot endorse his statement (pp. 123–38) that the volatile compounds have been the important factor in magmatic differentiation. This will be more closely treated in a later paper.

[*To be continued*]

THE PLEISTOCENE HISTORY OF THE LOWER WISCONSIN RIVER[1]

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INTRODUCTION

The Wisconsin River, rising among the glacial lakes in the northern part of the state of Wisconsin, flows almost due south nearly to Portage, where it turns and flowing westward for a distance of about 80 miles joins the Mississippi just south of Prairie du Chien (Fig. 1). It is this lower, east-west part of the river valley which is discussed in this paper. The terminal moraine of the Wisconsin glacial epoch crosses the valley just east of Prairie du Sac and marks not only the eastern boundary of the region here considered but also that of the driftless area. Since glacial drift is found in Iowa opposite the lower end of the valley, it may be said that the Wisconsin River traverses from east to west the entire driftless area. It is thus seen that drift remnants which are found in this part of the valley are of important significance in the history of ancient ice invasions in bordering regions.

These remnants of glacial drift in the valley fall naturally into two divisions: First, there are terraces of Wisconsin age: (*a*) remnants of the valley train sloping from the terminal moraine, where it crosses the valley near Prairie du Sac, to the Mississippi River, and (*b*) a lower terrace standing only 15 feet above the present river flood-plain; and second, standing well above the preceding terrace, are rock benches covered with much older drift. These upper benches have a gentle slope toward the east (Fig. 2).

PART I. OLDER DRIFT

Stated in the simplest terms, there are six areas of the older drift: (1) near Lone Rock, (2) near Muscoda, (3) from Muscoda to Boscobel, (4) from Boydtown to the Kickapoo River, (5) at

[1] Condensed from Ph.D. thesis submitted to the Department of Geology, the University of Chicago, 1920.

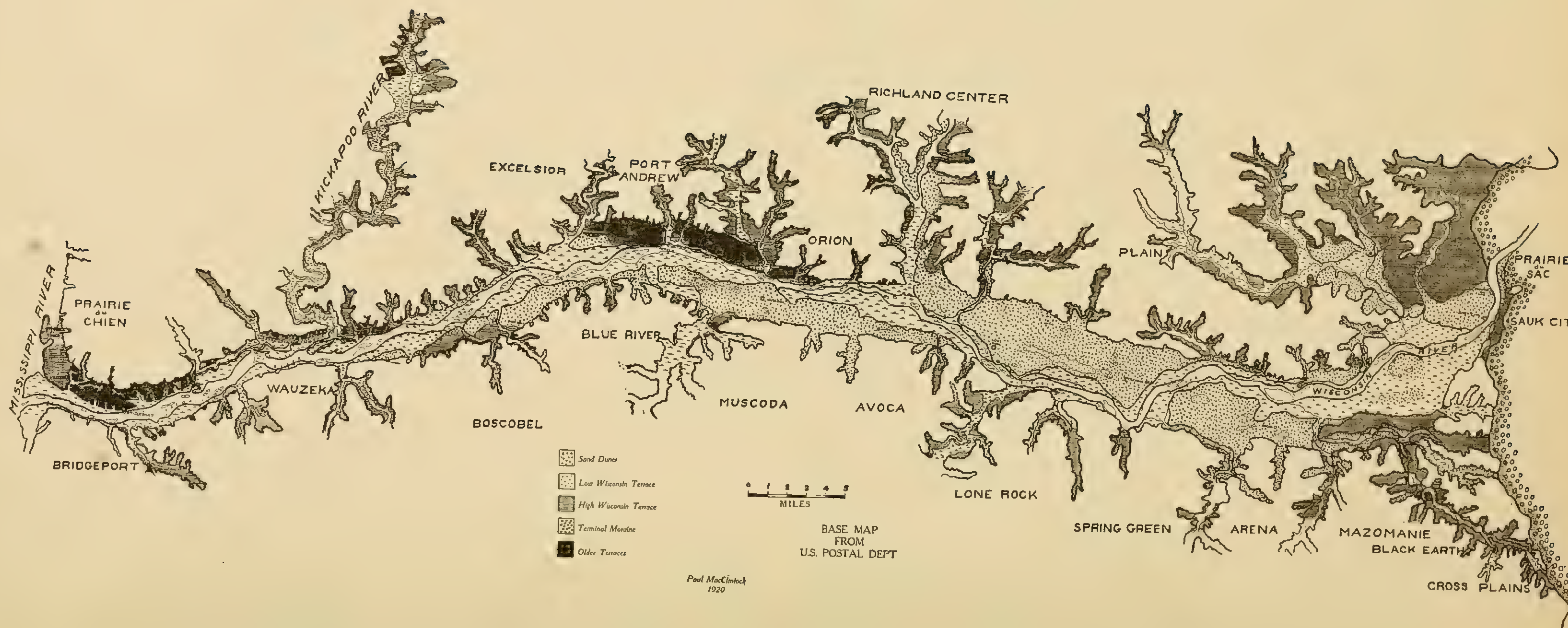
MISSISSIPPI RIVER
PRAIRIE du CHIEN
BRIDGEPORT
KICKAPOO RIVER
WAUZEKA
BOSCOBEL
EXCELSIOR
PORT ANDREW
BLUE RIVER
ORION
MUSCODA
RICHLAND CENTER
AVOCA
LONE ROCK
PLAIN
SPRING GREEN
ARENA
WISCONSIN RIVER
MAZOMANIE
BLACK EARTH
CROSS PLAINS
PRAIRIE du SAC
SAUK CITY
Sand Dunes
Low Wisconsin Terrace
High Wisconsin Terrace
Terminal Moraine
Older Terraces
0 1 2 3 4 5
MILES
BASE MAP
FROM
U.S. POSTAL DEPT
Paul MacClintock
1920

FIG. 1

Wauzeka, (6) at Bridgeport. The first four of these are similar in topography, constitution, and amount of weathering, while the last two differ from the others in that they contain not only much striated material (at Bridgeport) but also a large percentage of calcareous material.

I. SUBDIVISION

It appears from the evidence that the older drift is not all of the same origin or age.

a) A lithologic study of some 300 characteristic rock specimens collected from the different exposures, and examined in the laboratory, shows 37 common to Wauzeka and Bridgeport, 17 common to

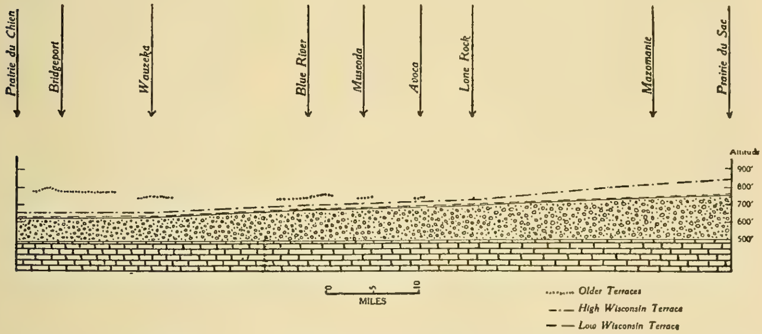

FIG. 2.—Profile of the Wisconsin River Valley from Prairie du Sac to Prairie du Chien showing the bedrock, the drift partly filling the valley, and the levels of the three terraces.

Orion (Port Andrew) and the nearest Illinoian drift at Verona, 9 miles southwest of Madison, 27 common to Orion and Wauzeka, and 25 common to Bridgeport and Iowa (near McGregor). These facts show that there is close similarity between the drifts of Illinoian age and that at Orion on the one hand, and between the drift at Wauzeka, Bridgeport, and Iowa on the other.

b) The drift at Wauzeka and Bridgeport contains much limestone and dolomite, while farther up the valley there is neither. Since the Illinoian and pre-Illinoian drifts east of the region contain calcareous material, it is likely that these terrace deposits in the mid-course of the valley originally contained the carbonates which have been subsequently leached.

c) There is well-developed cross-bedding at Blue River dipping westward, while at Wauzeka, less well-developed but still recognizable cross-bedding in sandy layers dips eastward (Fig. 3).

d) While there are numerous bowlders in the drift of the mid-course of the valley, there are more to be seen at Wauzeka and Bridgeport.

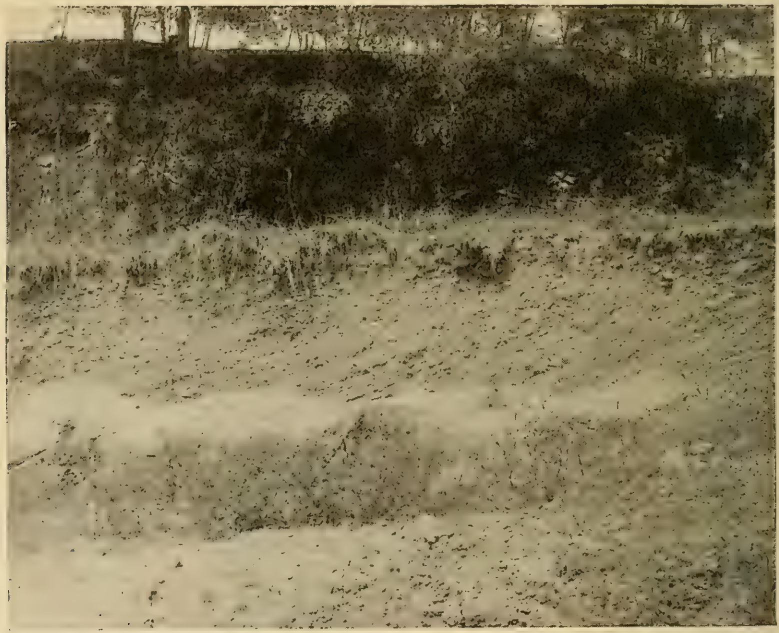

FIG. 3.—Westward dipping gravel on the high terrace two miles northeast of Blue River.

e) On the Bridgeport terrace the stones are not only more angular than elsewhere in the valley, but numerous subangular and striated ones are found. In fact these glaciated stones are as numerous on this terrace as in the till either in Iowa or at the eastern end of the region.

The suggestion from this evidence is that the drift in the mid-course of the valley is fluvio-glacial and from the east, while that at Bridgeport is glacial, and that at Wauzeka is fluvio-glacial and both the latter are from the west.

2. MID-COURSE DRIFT

a) *Origin.*—The cross-bedding at Blue River makes it evident that the drift in the mid-course was brought in from the east (Fig. 3). This being the case, the upper surface of these terrace deposits should slope conspicuously toward the west, for, while large bowlders so common in most of the exposures may have been carried in bergs, the mass of the material is fluvial and must have been transported by a glacial river—a river having powerful current and fairly steep gradient. A steep gradient may well be postulated for such a glacial river, for there appears, if the bedrock floor of the valley be considered, to have been down-warping at the eastern end of the region. The bedrock in the valley bottom near Prairie du Sac has an altitude of something less than 500 feet,[1] while at Prairie du Chien, near the mouth, its altitude is 490 feet, making a gradient of only two inches to the mile (Fig. 2). The preglacial river with so low a gradient as this could not have eroded so deep and narrow a valley as the rock bottom of this part of the Wisconsin Valley appears to be. The unavoidable inference is that the eastern end of the region must have been higher in preglacial and possibly early glacial times, and must have subsided before the last glacial advance. Data from neighboring regions also suggest that such warping has taken place.[2]

b) *Age.*—Old drift has been described on the eastern margin of the driftless area by Leverett, Weidman, and Alden,[3] and called by them pre-Illinoian in age. The absence of calcareous material in the old drift in the mid-course of the Wisconsin Valley, even where seen 10 and 12 feet below the surface, suggests that it is as old as Kansan and probably older, i.e., the outwash from the first ice advance.

3. WESTERN DRIFT

a) *Origin.*—The drift on the Bridgeport terrace must be either glacial or fluvio-glacial in origin. The large number of striated and

[1] W. C. Alden, *U.S. Geol. Surv. Prof. Paper 106* (1918), Plate II.

[2] W. C. Alden, *op. cit.;* F. Leverett, *Journal of Geology*, Vol. III (1895), p. 740; E. W. Shaw, *Bull. Geol. Soc. Amer.*, Vol. XXVI (1914), p. 67.

[3] F. Leverett, *U.S. Geol. Surv. Monograph 38* (1899), pp. 109–10; S. Weidman, *Wis. Geol. Surv., Bull. 16* (1907), p. 433; W. C. Alden, *op. cit.*, p. 168.

subangular stones found nowhere else in the outwash material of the valley, together with the patchy character of the drift, suggests deposition directly by the ice. If this view is correct the glacier must have extended from Iowa across the Mississippi into the lower end of the Wisconsin Valley.

On the other hand, at no place where this older drift occurs was a glacial pavement seen. The drift lies in most places on deeply eroded and weathered dolomite, while at other places several inches of blue-black clay, weathered from the bedrock, lies at the base of the brown drift. It is not strange that, in exposures so limited, no pavement was seen; none has been found in Iowa in this vicinity, where the ice is known to have stood to the very edge of the Mississippi Valley. It seems probable that if a tongue of ice projected into the Wisconsin Valley for a distance of 4 miles—a condition called for by this hypothesis—it would have been at least as wide as the mouth of the valley ($1\frac{1}{2}$ miles) so that its shoulders would have rested against the valley walls near the mouth, and have left there glacial material. Some material of this kind is seen for a distance of $1\frac{1}{2}$ miles north of the lower end of the Wisconsin Valley. It is however small in size, meager in quantity, and found not strictly on the shoulders but on the lower slopes at heights of never more than 100 feet above the flood-plain. Glacial material on slopes so steep as the shoulders present would not have remained there but would have soon been washed to the flat below.

The crucial points are: (1) the Bridgeport drift is much higher in altitude than any of the older drift farther up the valley, (2) it is composed of striated, subangular, and grooved material, and (3) it is both stratified and unstratified—the latter material indistinguishable from till. The conclusion then is that this drift is glacial in origin and was deposited by a tongue of ice. It seems clear that the drift at Wauzeka is the outwash material from the same ice invasion, for it is closely akin to the Bridgeport drift in many ways, has the lense and pocked structure of outwash material, and has a suggestion of eastward dipping cross-bedding (Fig. 4). None of this calcareous drift is found farther up the valley because the decline of this old valley train would have brought its top below the level of the rock benches where drift is now found.

This hypothesis involves a damming of the Mississippi River by the ice tongue at the mouth of the Wisconsin. Under this condition the Mississippi must then have flowed between this ice tongue and the northern wall of the Wisconsin Valley and thence eastward to the Rock River or more probably the Lake Michigan Basin. Such an eastward flowing river, if the bedrock divide near Portage had about the present altitude of 600 feet,[1] would have

FIG. 4.—View of the outwash material on the high terrace at Wauzeka showing lenses of sand in the gravel.

had a gradient of about 2.5 feet per mile, or a foot per mile greater than that of the present Wisconsin River. This suggests that the down-warping of the eastern part of the area, mentioned above, had already taken place. It seems, in fact, quite probable that this eastern part of the region was lower than it is at present, for post-Champlainic uplift and warping in the Great Lakes area probably raised the divide from some lower elevation to its present altitude. Since such down-warping as first mentioned has been found in

[1] W. C. Alden, *op. cit.*, Plate II.

neighboring regions, it seems well to note it here, and by so doing possibly to fix the date of the warping—after the first ice invasion at the east of the area and before the second invasion on the west.

Additional evidence of such a displacement of the Mississippi might be expected in old channels. In the eastern part of the valley, Wisconsin glaciation has destroyed any possible trace, while at the west the river was either displaced for so short a time, or subsequent erosion has been so great that there is no evidence of a channel occupied during the displacement. No channel is found in Jo Daviess County, Illinois, where a similar tongue of ice pushed across the Mississippi Valley from Iowa and left drift near Hanover.[1]

b) *Age*.—Two drift sheets, the Kansan and the pre-Kansan, are thought to be present in Iowa near the mouth of the Wisconsin River.[2] The western drift in the Wisconsin Valley must be correlated in age with one of these. The former drift sheet is less weathered than the latter, which is represented, according to present determinations, only by scattered and very much weathered erratics. Judging from the thickness (20 to 50 feet), and from the large content of limestone and dolomite, it seems most probable that the Bridgeport and Wauzeka drift is of Kansan age.

PART II. WISCONSIN DRIFT

1. The terminal moraine of the last glacial invasion extends southward from the Baraboo Range, crossing the Wisconsin River $1\frac{1}{4}$ miles northeast of Prairie du Sac. On the south side of the river it maintains a southerly direction to Black Earth Creek which it crosses $1\frac{1}{4}$ miles east of Cross Plains. North of the river this moraine is a belt showing morainic topography, while south of the river it is in most places a narrow distinct ridge strewn with bowlders. Where it crosses the river the section shows 60 feet of cross-bedded sand with small lenses of fine gravel, overlain, with a sharp contact, by 30 feet of till. The sharp contact shows no weathering. This sand may be outwash from an early Wisconsin moraine farther east or may be the outwash deposited in front of the advancing late Wisconsin ice.

[1] E. W. Shaw and A. C. Trowbridge, *Ill. State Geol. Surv. Bull. 26* (1916), p. 87.

[2] A. C. Trowbridge, *Bull. Geol. Soc. America*, Vol. XXVI (1914), p. 76.

2. Sloping gently westward from the moraine north of the river a sandy outwash plain extends to an irregular boundary against the sandstone hills of the country rock. The western edge is irregular, for the fluvio-glacial material is found up the valleys of Honey and Otter creeks. Of special interest are the erratics found in the south branch of Honey Creek as far west as Blackhawk and Plain. They lie on an upper terrace, corresponding in elevation to that of the outwash plain across the mouth of the creek at its eastern end. This position, 17 miles beyond the terminal moraine, implies that the bowlders were carried to their positions while frozen in blocks of ice floating on a lake.

Such a lake may have been formed in one of two ways:

a) The edge of the ice may have extended beyond the terminal moraine and dammed the mouth of Honey Creek. No evidence was found to substantiate this possibility.

b) As the outwash plain was being built, the glacial waters issuing from the ice-front between Prairie du Sac and the South Range swept their load southward across the mouth of Honey Creek. Outwash material may thus have dammed the mouth of Honey Creek, forming a lake upon which icebergs may have floated the bowlders. While this suggestion involves the difficulty of getting the bergs swept across the outwash plain and into the lake, it still seems the more probable of the two.

3. The valley train, now represented by terrace remnants, once filled the bottom of the valley from the terminal moraine to the Mississippi River. It was 90 feet above the present flood-plain near the terminal moraine, 30 feet in mid-course, and 40 feet at the western end of the valley. As this outwash deposit was growing, the glacial waters constantly deposited material across the mouths of the tributary valleys, causing them in turn to aggrade their channels. Terrace remnants of these slack-water deposits are to be seen in most of the tributary valleys, serving to project the level of the valley train even where it has been removed from the main valley by subsequent erosion.

The most easterly remnant of the original valley train lies near Mazomanie at the mouth of Black Earth Creek. It is an irregular area a mile wide by 6 miles long, separated from the south bluffs

by Black Earth and Halfway Prairie creeks. The surface of this area is gently rolling and marked here and there by patches of low sand dunes. This terrace level extends eastward into Black Earth and Halfway Prairie valleys while the two intervening shorter valleys have this high fill only at their very mouths. This relationship is of importance in connection with the problem, later to be considered, of the age of the terrace.

From Mazomanie for a distance of 30 miles to the west, the upper part of the valley train has been entirely removed from the main valley. The terrace level is, however, present in most of the tributary valleys; notably Blue Mounds, Wyoming, Otter, Pine, Eagle, and Kickapoo creeks. But there are several tributary valleys (see Fig. 1) lacking this terrace level, a fact whose significance is later to be considered.

The remnants of this level, the high Wisconsin terrace, are again found in the main valley near Muscoda and Blue River where the bench is protected by a subjacent ledge of sandstone against which the river is at several places flowing. At Boscobel a large terrace remnant lies against the south wall of the valley. In these latter terrace patches the material is smaller in size and contains fewer limestone pebbles than farther up the valley.

4. Twelve to 15 feet above the Wisconsin River flood-plain and extending short distances up the valleys of many of its tributaries there is an extensive sandy terrace—the low Wisconsin terrace. From the terminal moraine at Prairie du Sac to Wauzeka, a distance of 65 to 70 miles, it is nearly continuous in the main valley on one side of the river or the other, while from Wauzeka to the Mississippi it occurs only in small detached areas. Remarkable uniformity in height above the river is one of its most notable characteristics, for the variation is not more than a foot or two throughout the whole distance. A second notable feature is that the material, where seen in shallow cuts, is uniform in size and constitution through the whole length of the valley, being mostly sand with small pebbles scattered rather uniformly through the mass. The surface of this terrace is in general very flat, but in detail it is seen to have irregularities produced by the wind, such as sand dunes and "blowholes." Considerable dune areas are found in the neighborhood of Lone Rock and Spring Green. In fact, the whole terrace is so

sandy and so poor as farm land that it is called locally "Prairie" or "Barrens."

There are three possibilities to be considered in discussing the origin of the low terrace: It is either the valley train of the late Wisconsin ice advance or was cut from the early Wisconsin valley train by waters from a glacial lake, or is a combination of the two.

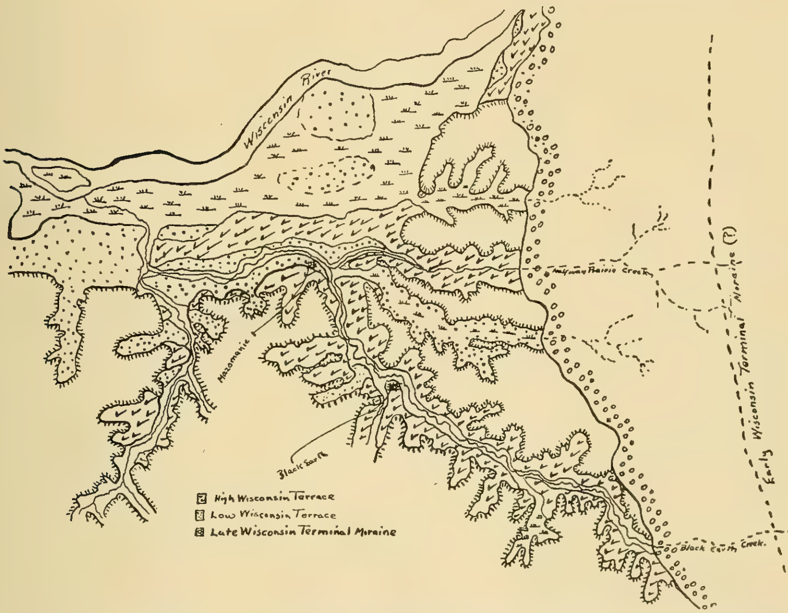

FIG. 5—Diagram showing the relation of the terraces in the four valleys east of Mazomanie. Black Earth and Halfway Prairie creeks contain the high terrace while the two shorter valleys do not.

a) Alden is of the opinion that the low terrace is the result of deposition by glacial waters from the late Wisconsin invasion, while the upper terrace resulted from the early Wisconsin advance.[1] The evidence is as follows: Of the four small valleys east of Mazomanie, the two longer ones contain the upper terrace while the shorter ones do not.[2] This, Alden interprets as meaning that the ice of the early Wisconsin invasion did not reach the heads of the shorter valleys, discharging its waters only through the longer ones and building in them the high terrace (Fig. 5).

[1] W. C. Alden, *op. cit.*, pp. 191–93 and 244–45.

[2] The northern one does contain several small patches (see Fig. 5).

Following the retreat of the early Wisconsin ice came a period of erosion during which part of the fill was cut away. The late Wisconsin ice advanced farther and stood across the heads of all four valleys, building valley trains at the level of the low terrace. At the same time the low terrace was being built in the main valley.

Evidence adverse to this suggestion must be summarized under several heads:

i) If deposited by glacial waters, the terrace should decline westward more rapidly than the present river, unless the western end had been raised by postglacial tilting. But, judging from the tilting of the glacial beaches of the Great Lakes, this latter possibility is unlikely.

ii) If deposited by glacial waters the material should be noticeably coarser at the eastern end grading to fine at the west. This is not the case.

iii) There are three conspicuous examples of small valleys containing only the low terrace, west of the farthest ice advance (just west of Black Earth, south of Arena, and west of Avoca), while there are but two such cases among the valleys heading in the terminal moraine, as previously cited. It would seem that the mere fact that two of the four valleys east of Mazomanie do not have the high terrace is not conclusive one way or the other. In fact, it would be just as plausible to suppose that there was but one Wisconsin advance in this region and that, since the longer valleys drained the ice both earlier and later than did the shorter ones, they received more outwash, and so were more aggraded. The thin terminal moraine crossing the valleys means a short stay of the ice-edge at this place, or poverty of débris in the glacier.

iv) No evidence was seen of weathering of the stratified drift underlying the till of the terminal moraine, as would be expected somewhere in the region if it were early Wisconsin and the till were late Wisconsin, since this interglacial interval is considered by many to be fairly long. The stratified drift may as well be outwash deposited by waters which flowed out in advance of the oncoming ice.

v) The evidence from the larger amount of leaching of the outwash plain, suggested by Alden and Weidman,[1] as showing that

[1] W. C. Alden, *op. cit.*, p. 192.

the high terrace is older than the terminal moraine and outwash of the low terrace, was not verified. For cuts on and directly west of the moraine show about the same amount of leaching as do the exposures farther west on the high fill.

vi) The high terrace marks a time of great filling, while the low one is much less important in this respect. Evidence from other regions has led to the generalization that the ice of the late Wisconsin substage was the most energetic of all the ice advances, building higher and more rugged moraines; eroding more deeply and more conspicuously; dumping more sediment into the drainage lines leading away from the ice-front, and so building larger valley trains. This line of evidence would point rather to the late Wisconsin than the early Wisconsin substage as the builder of the high terrace.

vii) Since erratics in Honey Creek Valley rest only on the high Wisconsin terrace, it seems clear that a glacial lake stood in this valley during at least part of the time when the slack-water fill of which these terraces are remnants was being deposited. It would be inferred that the lake was dammed during the maximum extent of the ice, rather than when the ice-edge stood farther east, as it did in early Wisconsin time if the early Wisconsin ice affected this immediate region. This piece of evidence suggests that the high Wisconsin fill in Honey Creek Valley was deposited when the ice-front stood at least as far west as Prairie du Sac.

The weight of this evidence is seriously against the possibility that the low terrace was deposited as a valley train of the late Wisconsin invasion.

b) When the ice-front of the Green Bay lobe had withdrawn east of the Portage divide, the ice-dammed lake, Jean Nicolet,[1] was formed with its outlet down the Wisconsin Valley. These outlet waters were clear, and probably cut the upper part of the valley train down to the level of the low terrace. Evidence that the low terrace was cut by waters from Lake Jean Nicolet follows.

i) The uniform height, 12 to 15 feet, of the terrace above the flood-plain all the way from the terminal moraine to the mouth of the valley, suggests strongly an erosional rather than a depositional origin.

[1] W. Upham, *Amer. Geologist*, Vol. XXXII (1903), p. 330.

ii) The material, in at least the upper few feet of the terrace, throughout the length of the valley is uniform in size, shape, and structure. The river having a uniform gradient would handle sediment of uniform size through its whole length. This would result in the coarser material in the eastern part of the high terrace, when cut by these outlet waters, being buried below several feet of finer re-worked material covering the low terrace.

iii) Its similarity to the Brule–St. Croix outlet of Lake Duluth is noticeable. This latter is also a broad sandy plain with dunes and blowholes upon its surface.[1]

iv) The low gradient, 1.75 feet per mile, for so large a volume of water, would favor a wide rather than a deep cut.

Against this mode of origin the following points may be registered:

i) It would be expected that the upper few feet of the terrace would be re-worked by the running water and the material therefor assorted. But this is, as a rule, not the case, for the pebbles are scattered indiscriminately through the sand.

ii) Weidman states, in relation to the Brule–St. Croix outlet that ". . . . Aside from cutting down a few drift dams that lay across the outlet, there was not much erosion."[2] It is possible, then, that there was not enough cutting by the waters of Lake Jean Nicolet to cut the upper terrace to the level of the lower one. However, the rapidity of cutting, depending upon the volume and the velocity of the river as well as the kind of material cut, may not have been the same in the two cases. So the slight amount of cutting of the Brule–St. Croix outlet would not carry a necessary implication against great cutting in the Wisconsin Valley.

iii) The relation of the terraces in the four tributary valleys just east of Mazomanie, previously discussed, is significant but not conclusive.

From the weight of this evidence, the low terrace appears to be a degradational level cut by waters from the glacial lake.

c) A third suggestion presents itself which combines the first and second in such a way as to obviate many of the difficulties

[1] Moses Strong, *Geology of Wisconsin*, Vol. III (1880), p. 387.

[2] Samuel Weidman, personal communication.

inhering in each. With the advance of the early Wisconsin stage, the outwash valley train was deposited. During the subsequent period of ice withdrawal, the pounded waters of the Fox River Valley flowed across the Portage divide and down the Wisconsin Valley, cutting away a large part of the valley train. This period must have been rather long, or erosion excessively rapid by a large and powerful river, for more erosion took place then than has taken place since the last withdrawal of the ice. This would not appear to be improbable, for, during this partial withdrawal, the ice may have dammed the lake for a much longer period of time than it did in the final deglaciation. Then when the late Wisconsin ice advanced to the region of Prairie du Sac, the outwash partially filled the channel cut below the early fill. Later, as the ice withdrew, the lake was again dammed east of the Portage divide and the waters flowed westward down the Wisconsin Valley, cutting the lower fill to the level of the low terrace. This would involve less cutting at any one stage than the first suggestion, and at the same time would allow the terrace to stand, as it does, at a constant elevation above the present river level, for the waters from the lake probably would cut to the same gradient as do those of the present Wisconsin River.

While the hypothesis of two Wisconsin advances will explain the presence of the high terrace in two of the valleys east of Mazomanie and its absence from the other two, it will not account for the absence of this high terrace in the tributaries farther down the Wisconsin River. And since it is evident that the former case can be explained on the basis of one advance into this region, the idea of two ice invasions in Wisconsin time may be discarded as needless.

SUMMARY

The terraces of Wisconsin age may be best explained on the hypothesis that they are connected with one glacial advance—that of the late Wisconsin ice-sheet—and that the lower terrace was cut from the higher by waters issuing from Lake Jean Nicolet.

PART III. THE PLEISTOCENE HISTORY

The first glacial invasion in Pleistocene time advanced on the eastern side of the region to a position somewhat east of the Wiscon-

sin terminal moraine. The eastern end of the region at this time stood relatively higher than it does now, so that the glacial waters flowing down the Wisconsin Valley had a steep gradient and transported coarse débris. The glacial drainage from at least a hundred miles of ice-front to the north must have flowed southward to the vicinity of Portage, and then westward down the Wisconsin River. In its course, along the ice margin, the river must have cut against the edge of the ice, at least in places, and must have broken off blocks of débris-laden ice, floating them into the Wisconsin Valley. Here many of them must have grounded and, upon melting, have deposited their loads. The adequate source of bergs, the abundant supply of glacial material, and the swift and powerful glacial river seem sufficient to account for the older drift deposited on the terraces of the mid-course of the valley. After the ice had stood long enough to build a valley train to a height of at least 75 feet above the present flood-plain in the mid-course of the valley, it withdrew and erosion cut away the valley train till all that remained were the terrace remnants on rock benches along the sides of the valley. It is not known how deeply this erosion progressed, but probably the valley was largely re-excavated.

At some time after this first valley train was built and before the next glacial advance, the eastern end of the region was depressed relative to the western end. A depression of 150 to 250 feet would not have been unlikely and would account for the phenomena observed.

The Kansan ice advanced across Iowa, crossed the Mississippi River in the neighborhood of Prairie du Chien, and projected a tongue of ice into the lower end of the Wisconsin Valley. The Mississippi was dammed, diverted into the Wisconsin Valley, and flowed eastward, carrying with it not only great quantities of coarse and fine outwash material, but abundant icebergs broken from the ice-front farther north as it encroached upon the Mississippi Valley. An eastward sloping valley train of coarse material was built. When the ice withdrew, erosion cut away the moraine and valley train, save where remnants are left on rock benches at Bridgeport and Wauzeka. The depth of this erosion is not known accurately,

but the valley was probably again re-excavated to about its maximum depth.

There are no terraces in the valley which correspond in age to the Illinoian drift found at the eastern end of the region, so the assumption is that the outwash from this glacial advance did not fill the valley high enough to be above the present surface of the river. The evidence of five well records[1] shows that at one time the valley floor stood, in the main and also the tributary valleys, 30 to 50 feet below its present level long enough to accumulate a bed of peat. It is probable that the outwash from the Illinoian invasion filled the valley only to this level, 30 to 50 feet below the present surface. Then ensued a period during which the vegetation accumulated on the swampy surface of this outwash.

During the Iowan epoch loess was blown on to the western part of the area, burying the drift with a blanket of eolian material.

In Wisconsin time not only the moraine at Prairie du Sac, but the valley train in the Wisconsin Valley, was deposited. As the ice withdrew east of the divide near Portage, ponding produced a lake which drained westward down the drift-filled Wisconsin Valley. This was for a time the main drainage for at least a hundred miles of ice-front lying toward the north, consequently a large quantity of clear water flowed down the valley. The upper part of the fill was largely cut away, leaving remnants which now constitute the upper terrace in the Wisconsin Valley. The down-cutting river reached grade at the level of the top of the lower terrace.

After the ice had withdrawn and the glacial lake was drained, the postglacial Wisconsin River cut away large parts of the lower terrace to form its present flood-plain.

[1] Well records which show peat 30 to 50 feet below the surface; fair grounds at Richland Center; schoolhouse 1½ miles northeast Richland Center; Bear Creek ¾ mile north of junction with Little Bear Creek; Little Bear Creek ½ mile north of junction with Bear Creek ¼ mile southwest of Leland.

ORIGIN OF THE TRIASSIC TROUGH OF CONNECTICUT

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The paper by Professor W. M. Davis on "The Triassic Formation of Connecticut"[1] has long been regarded as a masterpiece in geologic literature. So well was the work done that little has been added to the knowledge of the Newark formation in Connecticut since its publication. Professor Davis did not, however, reach a definite conclusion concerning the origin of the trough within which the Newark sediments collected. Two hypotheses have been most widely held to explain the origin of the depression. It is the purpose of this paper to state briefly the field facts which bear upon these hypotheses and to suggest a method of research which may aid in the solution of the problem.

The two hypotheses referred to are: (1) the depression was formed by a gradual bending downward of a canoe-shaped trough without faulting movements (Fig. 1), and (2) the depression was developed by faulting movements on each side of the depression sedimentation (Fig. 2). Both of these hypotheses were suggested by Professor Davis in his report.[2] The fundamental hypothesis may be modified by certain limiting conditions. Professor Davis was inclined to believe that the formation of the trough was not accompanied by faulting. He also held that the original area covered by the Newark deposit was not much greater than that over which the series outcrops today.[3] Professor Grabau, while agreeing with Professor Davis in part, believes that a vast geosynclinal wedge extended from the eastern folds of the Old Appalachian Mountains, and that the present areas "are mere erosion remnants

[1] *Eighteenth Annual Report, U.S. Geol. Surv.* (1897), Part II, pp. 1–192.

[2] *Ibid.*, pp. 37–38. [3] *Ibid.*, p. 191.

of once much more extensive deposits . . . . preserved by being faulted beneath the level of erosion."[1]

Again, Professor Davis suggests that the trough may have been developed by faulting movements on each side of the depression (Fig. 2), whereas Professor Barrell[2] has limited the faulting to the eastern border (Fig. 3).

It is believed that there is general agreement with Professor Davis' statement that the "ancient mountains of Western Upland must

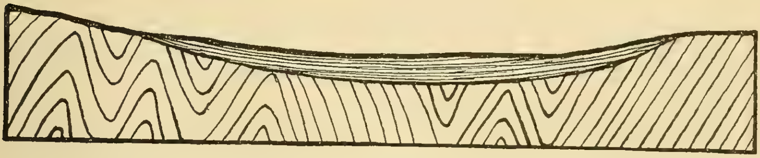


FIG. 1.—Diagram representing a depression formed by a gradual bending downward of a canoe-shaped trough, without faulting.

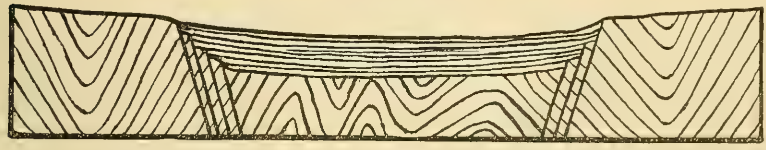


FIG. 2.—Diagram representing a depression developed by faulting which was continuous during the period of sedimentation.

have been worn down to a peneplain, or at least reduced to hills of moderate elevation and gentle slope, at the time the accumulation of the sandstones began."[3] It is further agreed that "the basement on which the Triassic strata rest" was worn "so low that no great additional amount of waste could be worn from it" had there not been depression of a central area accompanied by "correlated elevation of the adjoining areas on the west and east."[4]

Professor Davis goes on to say that "two suppositions may be made as to the character of these correlated elevations. The

[1] A. W. Grabau, *Text Book of Geology*, Vol. II, pp. 612–13.

[2] Joseph Barrell, "Central Connecticut in the Geologic Past," *Bulletin No. 23, Conn. State Geol. and Nat. Hist. Survey.*

[3] *Eighteenth Annual Report, U.S. Geol. Surv.*, Vol. II, p. 25.

[4] *Ibid.*, pp. 37–38.

trough may have been bent down between two arched areas on either side, as in Figure 1, or the trough may have been faulted down between two uplifted blocks alongside of it, as in Figure 2. While it did not seem advisable to make a final choice between the alternatives, the conditions illustrated by Figure 1 were favored, chiefly because the centripetal dips there shown would give, after general eastward tilting with more or less faulting, moderate dips for the lower strata in the east and stronger dips for the same strata in the

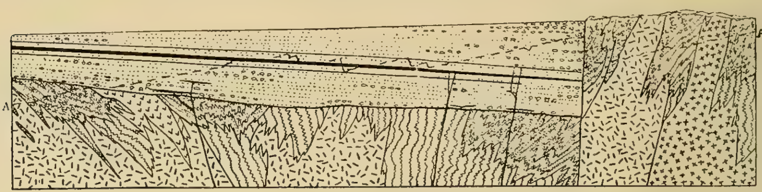


FIG. 3.—(After Barrell)

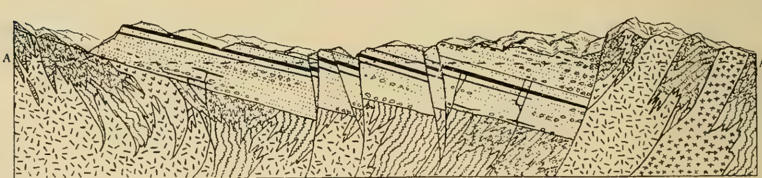
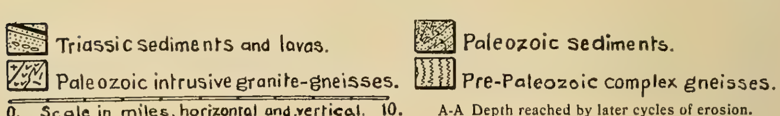


FIG. 4.—(After Barrell)



west. Professor Davis states that the field evidence showed an average dip to the east for the basal beds of 20° to 30° along the western border, and seldom more than 20° to the east for the analogous beds where exposed along the eastern.[1] His section, so widely copied in textbooks (Fig. 5), is therefore based on Fig. 1.

Professor Barrell, in his well-known study of "Central Connecticut in the Geologic Past," gives his conception of the origin of the depression. His idea is illustrated by Figures 3 and 4. A marginal fault of gradual development along the east side of the Connecticut

[1] *Eighteenth Annual Report, U.S. Geol. Surv.*, Vol. II, p. 39.

FIG. 5.—Sections across the Connecticut Valley Triassic. The upper section shows the present attitude of the formation as tilted and faulted. The parts which have been removed by erosion are restored. The lower section shows the supposed attitude of the formation before the tilting and faulting. (The shading with parallel lines does not represent planes of stratification.) From *Bulletin No. 6, Connecticut State Geological and Natural History Survey*, after Davis' figure in *Eighteenth Annual Report of U.S. Geological Survey.*

depression tilted the accumulating sediments toward the east and quickened the streams. Later smaller faults broke the trap flows and initiated the present topography (Fig. 4).[1] Professor Barrell supported his conception by the one statement that "the dominant segregation of conglomerates near the eastern margin is even more marked in the beds above the lava flows than in those below, and this greater average coarseness of the upper sediments indicates the intermittent regrowth of the mountains whose perennial waste kept supplying material for the basin."[2]

For reasons which will now be briefly stated the writer believes that Barrell's diagram represents most accurately the structure of the Connecticut depression during the Triassic.

1. A warping movement that distorts a peneplain surface without faulting must proceed very slowly. It is difficult to imagine that such a movement would revive the streams flowing into the Connecticut basin and cause them to transport bowlders of such a size as may be found not only in the edge but also toward the center of the trough. Cobbles 6 or 8 inches in diameter are found near the center of the valley, north of Meriden.[3]

2. Arkoses are common along the western border of the basin but are almost lacking along the eastern border, whereas coarse conglomerates are common along the eastern border but are seldom found along the western border. The inference is that the streams from the west were carrying the exfoliation products of a desert topography, but those from the east were carrying bowlders snatched from the wall of a growing fault scarp.

3. A consideration of the geometry of the geosynclinal hypothesis of Davis and the fault-monoclinal hypothesis of Barrell leads to conclusions which are more favorable to the latter. In Figures 6 and 7, let W represent the width of the Connecticut Valley. In northern Connecticut this width is approximately 21 miles; at Middletown it is 17 miles, or, if the Pomperaug Valley area is included within the larger basin, the width becomes 33 miles. Let D represent the depth of sedimentation within the basin. Compe-

[1] *Bulletin No. 23, Conn. State Geol. and Nat. Hist. Survey*, p. 28.

[2] *Ibid.*, p 29.

[3] *Eighteenth Annual Report, U.S. Geol. Surv.*, Part II, p. 33.

tent opinion places this thickness between 12,000 and 13,000 feet or between $2\frac{1}{4}$ and $2\frac{1}{2}$ miles. Let a represent the angle of dip developed in the basal beds by the gradual depression of the trough. At the sides of the geosnycline the actual angle would be greater than that indicated whereas, at the center, the beds would be flat, since the basin would be concave (Fig. 5). In either Case I (Fig. 6) or Case II (Fig. 7) it should be noted that the beds laid down at

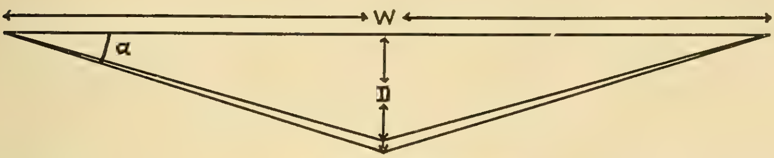


FIG. 6.—

Width	Depth	a
17	$2\frac{1}{4}$	$14\frac{1}{2}$
17	$2\frac{1}{2}$	$16\frac{1}{2}$
21	$2\frac{1}{4}$	12
21	$2\frac{1}{2}$	$13\frac{1}{4}$
33	$2\frac{1}{4}$	$7\frac{3}{4}$
33	$2\frac{1}{2}$	$8\frac{3}{4}$

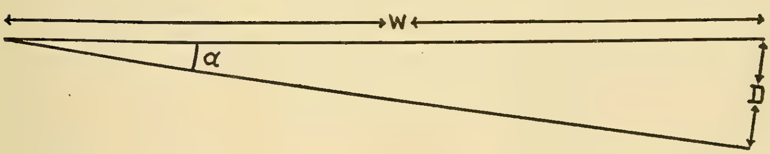


FIG. 7.—

Width	Depth	a
17	$2\frac{1}{4}$	$7\frac{1}{2}$
17	$2\frac{1}{2}$	$8\frac{1}{4}$
21	$2\frac{1}{4}$	$6\frac{1}{4}$
21	$2\frac{1}{2}$	7

the close of the period of sedimentation were approxiamtely horizontal, a fact overlooked by some writers. The diagrams are drawn to scale for a width of 17 miles and depths of $2\frac{1}{4}$ and $2\frac{1}{2}$ miles, respectively.

Whether the geosynclinal or the fault-monoclinal hypothesis be accepted, the present dips of the sediments of the basin were produced at the time of the post-Triassic faulting movements which tilted the rocks to the east. It would be advantageous to compare

the dips of the beds at the same horizon on the two sides of the trough, but only basal beds are exposed on the western side of the valley and upper beds on the eastern side. It is, however, possible to compare the known dips of the upper beds to the east with the dips of the basal beds to the west. Allowing for an erosion of 500 feet, the beds at the eastern side of the valley cannot lie far below the top of the series. Their original attitude at the close of the Triassic sedimentation was approximately horizontal. In the case of the geosynclinal hypothesis there may have been a slight dip to the west; in the case of the fault-monoclinal hypothesis, possibly a slight dip to the east. At present they have an average dip of 15° to 20° to the east. It is difficult to believe that the post-Triassic tilting was very dissimilar on the two sides of the valley. If it is assumed that the present dip of the upper beds was developed entirely at the time of the post-Triassic faulting, and that the tilt was, therefore, approximately 20° to the east, then, by adding 20° to the angle α, the present angle of dip of the basal beds at the western side of the valley should be obtained. Davis (see above) states that the average dip of the basal beds on the western side of the valley is 20° to 30°. In Case I (Fig. 6) by the foregoing method, the dips should be from 30° to 40°. In Case II (Fig. 7), angles from 20° to 30° are to be expected. It is true that, if the Pomperaug Valley area is included within the main basin, the results are inconclusive, but few authorities believe the original basin was much larger than it is today.

Assuming that the present dip of the upper beds of the Newark series at the eastern side of the valley represents the approximate angle of tilt to the east developed at the time of the post-Triassic faulting, then referring to Davis' diagram (Fig. 5), and conceiving that the present width of the valley was its approximate width in the Triassic period, in Case I the present dips should vary only slightly from the east toward the center of the valley, averaging perhaps a little lower about midway between the two points, but they should rise to a maximum at the western border. No normal dips near the center should be greater than the dips at the eastern border. In Case II there should be a progressive increase in dip

from the eastern to the western side of the valley.[1] The data concerning the strikes and dips within the Connecticut trough have never been assembled. Professor Davis' general statement quoted above would lead one to suppose, however, that there is an increase in the dips from the eastern toward the western side of the depression.

4. Pebbles in the upper conglomerates at the eastern border of the basin are known to be similar to rocks exposed at the very edge of the eastern upland. This condition is especially true near Lake Quonnipaug in Durham, Connecticut. East of the lake a chlorite schist, which is not common within the metamorphic rocks of the upland, outcrops for a mile or two. West of the lake the coarse "fan-glomerates" are filled with pebbles of this rock. The evidence indicates that the eastern limit of the Newark formation is at its ancient boundary, as Barrell's hypothesis would postulate, and that the basin sediments never extended over the eastern upland. If the eastern and marginal fault developed after the period of sedimentation, the chlorite schist at Lake Quonnipaug could not have been exposed to erosion at the time the "fan-glomerates" were being deposited.

5. The abundant development of those rocks so aptly named "fan-glomerates" by the western geologists along the eastern side of the basin is, in itself, strong evidence of the early initiation of faulting movements along this boundary. Such conglomerates are common throughout the exposed thickness of the Totoket block, but are not known on the western side of the valley.[2]

6. Finally, there is good evidence of the localization of vulcanism along the eastern fault line long before the end of the period of deposition within the basin. The writer has recently discovered a volcanic neck, in the southern part of Durham, north of Totoket Mountain, which lies within a stone's throw of the eastern fault margin.

[1] Excessive dips to the east are known near the eastern boundary fault. They are in the opposite direction from the drag dips which one would expect in this vicinity and have not been explained.

[2] Cf. C. R. Longwell, *Amer. Jour. Sci.*, IV (1922), 234–35.

For the reasons stated, the writer conceives of the Triassic basins of eastern Canada and the United States as a series of troughs of the basin range type which were developed during the collapse of the ancient land of Appalachia after the Appalachian mountain-building episode.

The Vale of Eden at the western base of the Pennine escarpment in northern England offers an interesting parallel to the inferred structure of the Connecticut Valley. Kendall has described the geology of the vale as follows:

> The succession in the Vale of Eden is of particular interest from the evidence that it furnishes of the physical conditions of the period and their changes. The valley is bounded on the east by the Pennine escarpment which owes its existence to a tremendous series of faults truncating the Permian and later rocks. The succession from west to east is: Carboniferous Limestone and Millstone Grit, covered unconformably by massive calcareous conglomerates, "Lower Brockram," usually dolomitized; bright red Penrith Sandstone about 300 m. (1,000 ft.); "Upper Brockram" interbedded in the upper part of the Penrith sandstone; Hilton Plant Beds with *Noeggerathia*, 45 m. (150 ft.); Magnesian Limestone 0–6 m. (0–20 ft.); Marls with gypsum having, locally, a basal conglomerate, 90 m. (300 ft.); St. Bees Sandstone (Trias) 600 m. (200 ft.)
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> . . . .
>
> The materials of the Lower and Upper Brockrams respectively furnish evidence of contemporaneous movement of the adjacent fault zone. The Lower Brockram consists exclusively of fragments of Carboniferous Limestone and the writer (Kendall) infers that it represents gravel-fans washed by torrential rains from the uplifted fault country, when the displacements had exposed only that division of the Carboniferous series. The Upper Brockrams were laid down after the deposition of 300 m. (1,000 ft.) of Penrith Sandstone, which should have covered up an equivalent portion of the faulted area, yet these Brockrams consist in large measure of the Basement Conglomerate of the Carboniferous series, with occasional pebbles of the underlying Ordovician rocks. This is interpreted to mean that between the formation of the two Brockrams a great further movement of the faults took place bringing the base of the Carboniferous up within the action of surface erosion.[1]

The eastern upland of Connecticut consists of such a tangle of metamorphic rocks that the rock succession is difficult to interpret.

[1] "The British Isles," *Handbuch der Regionalen Geologie*, Band III, Abteilung 1, p. 188. The writer is indebted to Professor Fearnsides, of Sheffield University, for calling his attention to the parallelism here described. "Brockram" is a local term used in the Vale of Eden for the rock known to the western geologists as a "fanglomerate."

However, the description of the geology of the Vale of Eden suggests a possible problem in sedimentation. A detailed study of the rocks of the eastern upland near the fault zone, combined with a microscopic study of the Anterior, Posterior, and Upper sandstones of the Connecticut Valley deposits might yield further evidence of the progressive growth of the eastern fault during the period of sedimentation.

IN SUPPORT OF GARDNER'S THEORY OF THE ORIGIN OF CERTAIN CONCRETIONS[1]

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In an article in the *Journal of Geology*, Gardner[2] has maintained that certain concretions are formed in supersaturated or overloaded water carrying fine clay particles. He believes that the particles are pressed together and are gathered in lumps just as the finely disseminated particles of butter are gathered together in churning and that these particles grow by accretion and gain their spherical form by being rolled along the bottom. He bases his opinion on observations of aggregations of mud balls in the bed of a stream after a flood in the Rio Chaco region of the San Juan Basin, New Mexico.

In the summer of 1921 the writer observed similar phenomena in the bed of the North Fork of the Red River, Beckham County, Oklahoma. As a result of a series of severe rains, this river, which is usually an insignificant stream flowing in sand-choked channels, had been flowing bank full. After the flood had subsided the writer observed on one of the sandy flats in the river bed a remarkable collection of clay aggregations similar to those described by Gardner. They consisted both of clay balls and cylinders, the former being much more numerous. The balls varied from less than an inch to about six inches in diameter. The cylinders were from four to six inches in diameter and a foot or more in length. Both balls and cylinders were composed of fine clay, with a small amount of sand and gravel in them or imbedded in the outer portion. The cylinders were apparently the result of two balls becoming stuck together and being rolled along the bottom, as several cases were observed showing the steps in this process. The considerable

[1] Published by permission of the Director of the Oklahoma Geological Survey.

[2] J. H. Gardner, "Physical Origin of Certain Concretions," *Jour. Geol.*, Vol. XVI (1908), pp. 442–58.

number of these aggregations at the place described seemed to be due to the fact that the flat was on the inside of a rather sharp bend where the current would be slackened.

FIG. 1.—Concretionary-like aggregations of fine clay deposited on a sandy flat in the bed of the North Fork of the Red River, Oklahoma, during a flood.

From the very perfect resemblance of these clay aggregations to ordinary concretions and the rather large number of them found after this one flood, the writer is inclined to agree with Gardner that this method of formation of concretions may be more common than is ordinarily supposed.

Figure 1 gives some idea of their size and distribution.

MUD CRACKS ON STEEPLY INCLINED SURFACES

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It is generally accepted that well-developed mud cracks or desiccation fissures are formed only on level surfaces that have been covered by shallow stands of water. Hence the presence of this phenomenon would be supposed to indicate level, low-lying mud flats; estuarine flood-plain, or playa in origin.

In the spring of 1922 it was my fortune to observe at Williamstown, Massachusetts, well-defined mud cracks in what I believe to be an atypical position. A small stream had undercut a bluff composed of finely laminated glacial-lake clays. Down the face of this bluff several mud streams had flowed, solidifying before reaching the brook. The surface of these mud streams was seamed with sun cracks which reached depths exceeding 8 inches, and whose intersections produced irregular polygons varying from 6 to 18 inches across. Clinometer readings carefully taken on those portions of the surface which exhibited the best-defined polygons ranged from 11° to 38°, with an average of about 22°. Some of the best polygons appeared on the steeper slopes.

Had any one of these mud flows been covered by later deposits and induration taken place, the presence of these sun-cracked polygons along the bedding-plane would have unquestionably been taken as evidence that it marked the contact between two horizontally deposited beds of clay. While the above-noted phenomena may not be at all unusual, it would seem that sufficient attention has not been called to occurrences of this type which might lead to serious stratigraphic errors after consolidation of the inclosing sediments.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Schlossmacher, K. "Die Sericitgneise des rechtsrheinischen Taunus," *Jahrb. d. Preuss. Geol. Landesanst., f. 1917*, XXXVIII (1919), Th. 1, 374–433, pl. 1, figs. 2.

The sericite-gneisses of the Taunus are dynamo-metamorphosed quartz-keratophyres and felso-keratophyres. Ten chemical analyses are given, of which four are new. A general description and a discussion of the chemical relationships are followed by descriptions of the various localities.

Schlossmacher, K. "Ein Verfahren zur Herrichtung von schiefrigen und lockeren Gesteinen zum Dünnschleifen," *Centralbl. f. Min. Geol., etc.*, 1919. Pp. 190–92, fig. 1.

The usual method of boiling porous and schistose rock fragments in Canada balsam is not efficient. Here is described an apparatus by means of which the pore spaces in the rock may be filled with balsam. A tube with a stoppered side opening is partially filled with balsam, placed in a water bath, and the air exhausted. Any time thereafter chips to be sectioned are placed in the side tube, the air is exhausted, the tube is tilted so that the chip falls into the balsam where it is left until the bubbles cease.

Schlossmacher, K. "Keratophyre und ihre dynamometamorphen Äquivalente aus der Umgegend von Bad Homburg im Taunus," *Jahrb. d. Preuss. Geol. Landesanst. f. 1919*, XL (1920), Th. 1, 460–505.

The metamorphic rocks of the Taunus are keratophyres and soda-keratophyres; tuffs were nowhere found. Detailed petrographic descriptions and two new chemical analyses are given.

Schlossmacher, K. "Einige nichtmetamorphe paläovulkanische Eruptivgesteine aus dem Vordertaunus," *Zeitschr. d. Deutsch. Geol. Gesell.*, LXXII (1920), 25–27.

Unmetamorphosed paleovolcanic albite-trachytes and trachy-andesites, that is, keratophyres and keratophyre-porphyrites, are described from eight

localities. The phenocrysts are usually albite, in two occurrences orthoclase with intergrown albite; the groundmass is trachytic albite with small amounts of magnetite, chlorite, and a little sericite.

SCHNEIDERHÖHN, H. "Die Methoden zur mikroskopischen Untersuchung kristallisierter Körper," *Handbuch der mikroskopischen Technik*, Stuttgart, X (1914), 45–94, figs. 68.

Gives a brief but very good summary of petrographic-microscopic methods, well illustrated by figures. Attention is called to the fact that these methods are applicable not only to the determination of rocks, but that they may be used in the determination of natural and artificial salts, synthetic minerals, cement, etc.

SCHNEIDERHÖHN, HANS. "Über Methoden, um rasch und einfach aus Photographien Strichzeichnungen herzustellen," *Senckenbergiana*, I (1919), 190–93, figs. 2.

While this is not a petrographic article, the method here given for rapidly reproducing photographs may be of interest to petrographers, especially in these days of poor print-paper. A developing-paper print of the thin section or other petrographic subject is "inked-in" with waterproof ink. It is then immersed in subdued light for a few minutes in acid hypo, and then, without washing, placed in a rather concentrated solution of about equal parts copper sulphate and potassium bromide. In a few minutes the silver image will become altered to a yellowish image of silver bromide. When of a yellow color, it is washed for a few moments and re-immersed in the hypo until the yellow color disappears and leaves a white background. Without first immersing in hypo the operation is somewhat slower. Instead of copper sulphate, potassium ferricyanide may be used. A second method, less desirable on account of the poisonous nature of the material, but more rapid, is to dissolve the silver in a dilute solution of potassium cyanide. The print should be thoroughly washed afterward.

SCHNEIDERHÖHN, HANS. "Die mikroskopische Untersuchung undurchsichtiger Mineralien und Erze im auffallenden Licht und ihre Bedeutung für Mineralogie und Lagerstättenkunde," *Neues Jahrb.*, B. B. XLIII (1920), 400–438.

Here is a most excellent summary of work done on the determination of opaque minerals by means of incident light under the microscope. A long bibliography is given.

SCHNEIDERHÖHN, HANS. "Beiträge zur Kenntnis der Erzlagerstätten und der geologischen Verhältnisse des Otaviberglandes, Deutsch-Südwestafrika," *Abhandl. d. Senckenbergischen Naturf. Gesell.*, XXXVII (1921), 221–321. Figs. 16, figs. 40 in photogravure, and colored map 1.

The greater part of this report is economic and geologic. Only a few igneous rocks are mentioned, namely, aplite, olivine and mica kersantites, and microgranite. The aplite occurs in a dike-like mass widening into lens-shaped masses in several places. It is cut by the younger kersantite. The microgranite forms a laccolite intruded between strata of the dolomite, and in all probability was derived from the same source as the aplite which may represent the channels through which the larger mass was intruded.

SCHÜRMANN, H. M. E. "Beiträge zur Petrographie der östlichen arabischen Wüste Ägyptens," *Centralbl. f. Min., Geol., etc.*, 1921, 449–58, 481–90.

Very brief descriptions are given of the various igneous rocks of Gebel Mogul, between Gebel Mogul and Um Dalfa, and between Gebel Gharib, Gebel Dara, and Gebel Mogul. Neither chemical analyses nor modal percentages are given, though the various minerals are named. The rocks described are various granitites, pegmatitic granite, hornblende-syenite, and tonalite as plutonic rocks occurring in stocks; pneumatolytic granite, granite-pegmatite, quartz-diorite, and quartz-augite-diorite, plutonic rocks in dikes; pegmatite, graphic-granite, quartz, aplite, riebeckite-aplite, quartz-bostonite, malchite, minette, augite-kersantite, amphibole-vogesite, granite-porphyry, riebeckite-granite-porphyry, and quartz-diorite-porphyrite in dikes; and the following extrusive rocks, also in the form of dikes: granophrye, quartz-porphyry, riebeckite-quartz-porphyry, felsite-porphyry, various porphyrites, andesite, diabase-porphyrite, and diabase.

SCHUSTER, ERNST. "Calcitführende Auswürflinge aus dem Laacher Seegebiet," *Neues Jahrb.*, B. B. XLIII (1919), 295–318, pls. 2.

The calcite-rich ejected blocks of the Laacher Sea region which occur in the leucite-phonolite-tuff are alkali syenites which must have formed the country rock in the deeps. The calcite is regarded as a magmatic mineral, as is also cancrinite and the rare calcium apatite. The rocks may be called calcite-pegmatites and calcite-syenites. In other fragments melilite was developed as well as calcite.

SEDERHOLM, J. J. "On Synantetic Minerals and Related Phenomena. (Reaction Rims, Corona Minerals, Kelyphite, Myrmekite, etc.)," *Bull. Comm. Geol. Finlande,* No. 48, 1916. Pp. 148, pls. 8, figs. 14.

Synantetic minerals are those which are characteristic at the contact between two definite minerals in igneous rocks, kelyphite rims being one form. Myrmekite is applied to intergrowths of plagioclase and vermicular quartz. In this paper the various forms and the different minerals occurring are discussed in great detail, and the literature is fully summarized.

SHAND, S. J. "The Pseudotachylyte of Parijs," *Quart. Jour. Geol. Soc.*, LXXII (1917), 198–221, pls. 4, figs. 13.

In the granite from the neighborhood of Parijs, Orange Free State, there occur abundant veins and networks of a dense black rock, to which, from its resemblance to tachylite, the name pseudotachylite is given. Numerous sketch maps and two photographs show the nature of the occurrence in the field, and eight photogravures show the appearance as thin sections. The rock is very opaque, due to innumerable inclusions of very fine black specks of magnetite. In some of the widest veins there is less magnetite but many polygonal spherulites of dark-brown color in a felt of feldspar-microlites. Several analyses are given. The writer concludes that the pseudo-tachylyte originated from the granite itself through melting, which was caused, not by shearing, but by shock or gas-fluxing.

SHAND, S. J. "The Principle of Saturation in Petrography," *Geol. Mag.*, I (1914), 485–93; II (1915), 339–40.

Mr. Shand replies to certain critics of his system of classifying rocks on the basis of saturated or unsaturated minerals. (The former minerals are those which are stable in the presence of free silica under magmatic conditions, the latter those that are unstable.)

SHAND, S. J. "A System of Petrography," *Geol. Mag.*, IV (1917), 463–69.

Gives further ideas as to desirable features in a classification of rocks. Shand proposes the following factors: (1) degree of saturation, giving five divisions; (2) the double ratio of Or-Ab-An, giving about eight families within each division; (3) the color ratio, giving from two to ten, but preferably four groups in each family; (4) crystallinity, giving two sub-groups within each group; (5) ratios of specific minerals or groups of minerals, giving the types to which "specific" names will be attached; (6) trivial characters of mineralogy and texture, giving varieties.

Shand, S. J. "The Norite of the Sierra Leone," *Geol. Mag.*, V (1918), 21–23.

Describes two norites from Sierra Leone. One an olivine-rich norite, belongs to 2312 (new form) of the reviewer's classification; the other melanocratic, and without olivine, belongs to 3312.

Shannon, Earl V. "Petrography of Some Lamprophyric Dike Rocks of the Coeur d'Alene Mining District, Idaho," *Proc. U.S. Nat. Museum*, LVII (1920), 475–95, pls. 3.

The various dike-rocks from the Coeur d'Alene district, collected by Ransome, Calkins, and Umpleby, are here classified and described. Among the rocks are various minettes, spessartites, and vogesites, and one odinite. From the widespread occurrence of these dikes the conclusion is reached that the district is underlain by a granitic batholith which is so far down that none of the complementary aplite reached the surface. The dikes and ore veins belong to substantially the same period.

Skoetsch, Carl. "Die Einschlüsse in den Basalten zwischen Godesberg und Remagen," *Centralbl. f. Min., etc.,* 1921, 353–63.

In this paper are described all the different minerals which have been found in inclusions in the basalts of this region, as well as their mode of origin, and the alterations produced in them by the basaltic magma.

Smith, W. Campbell. "Riebeckite-Rhyolite from Northern Kordofan, Sudan," *Mineralog. Mag.*, XIX (1920), 48–50.

Describes a riebeckite-rhyolite from which certain ancient stone implements found at Beraeis are made. Two specimens of tinguaitic dikes from Kadoro, described by Linck, represent the only previously mentioned soda-rich rocks in Kordofan.

Spangenberg, K. "Die Einbettungsmethode," *Fortschr. d. Min. Krist. u. Petr.*, VII (1920), 397–458.

Under "Immersion Methods" are included all those methods for determining refractive indices based upon certain appearances at the contact between a known and an unknown medium. Three groups are discussed: (1) Disappearance of the border, (2) Töpler's method of inclined illumination (often spoken of as Schroeder van der Kolk's method); (3) Becke's method of raising or lowering the tube of the microscope. A general summary is given of all methods, the reasons for the phenomena are discussed, the relative accuracy shown, and the cause of variation under different conditions pointed out.

SPANGENBERG, K. "Einige Anwendungen und Erweiterungen der Einbettungsmethode," *Centralbl. f. Min., etc.*, 1920, 352–62, 406–14.

Gives various applications of the immersion method.

STEIDTMANN, EDWARD. "Origin of Dolomite as Disclosed by Stains and Other Methods," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 431–50, pls. 7.

Most dolomites were deposited in the sea. A minority were formed by the replacement of limestones by underground waters. Pure dolomites and limestones are far more abundant than mixed beds of limestone and dolomite. The occurrence of calcitic casts in dolomite, or of hollow casts bounded by perfect molds, indicate that the casts were deposited in dolomite. Dolomite rhombs, imbedded in a hornlike impervious mass of fine-grained marine calcite, were evidently formed in the ooze contemporaneously with the calcite.

TARR, W. A. "Oölites in Shale and Their Origin," *Bull. Geol. Soc. Amer.*, XXIX (1918), 587–600, pls. 2, figs. 2.

Describes certain oölites found in shale in the Wind River Mountains, near Lander, Wyoming. They are believed to be due to direct precipitation of colloidal silica by the electrolytic and saline character of the shallow waters into which they were introduced by streams from the adjacent land.

TARR, W. A. "Origin of the Chert in the Burlington Limestone," *Amer. Jour. Sci.*, XLIV (1917), 409–52, figs. 13.

Believes the widespread chert which occurs in the Burlington formation of Mississippian age has been formed from colloidal silica derived from inflowing streams and deposited by electrolytic action. The ellipsoidal form of the chert is attributed to the flattening of the colloidal mass under its own weight and later by the weight of overlying sediments.

TILLEY, C. E. "The Petrology of the Granitic Mass of Cape Willoughby, Kangaroo Island, Part I, *Trans. Roy. Soc. South Australia*, XLIII (1919), 316–41, pls. 2, sketch maps 2.

The granitic rocks of Cape Willoughby, Victor Harbor, and Port Elliot are thought to be chonolites connected below with a single batholith. They were intruded at the close of the orogenic movements in the region. The dominant rock is granite with minor intrusions of aplite and pegmatite. Interesting rocks are the albitites, quartz-albitites, and muscovite-albitites, which are regarded as the final differentiates from the residual magma. The first rock

consists essentially of albitite, with accessory apatite, zircon, and rutile, and with small amounts of muscovite and quartz. The albitite has the character of the "chequer" albite of Flett. The quartz-albitite is similar to the preceding but contains a blue opalescent quartz. The muscovite-albitite contains essential muscovite, some of which is regarded as primary, though some is secondary. The amounts of quartz and muscovite are not stated. The first and third rocks belong to 1112 (new form) of the reviewer's system, the second is 118 if the amount of quartz is over 5 per cent, as it presumably is since these rocks are contrasted with quartz-bearing albitites.

TILLEY, C. E. "The Occurrence and Origin of Certain Quartz-Tourmaline Nodules in the Granite of Cape Willoughby," *Trans. Roy. Soc. South Australia,* XLIII (1919), 156–65, pls. 2.

Certain nodules, consisting essentially of quartz and tourmaline, occurring in an aplite intrusive in granite, are considered as having developed by the replacement of albite and microcline by tourmaline. Says the writer: "Microscopic and other evidence tends to show that they are strictly penumatolytic products. In the slides is to be seen the very act of replacement of feldspar by tourmaline."

TSUBOI, SEITARŌ. "On the Determination of the Limiting Values of the Medium Refractive Index of a Finely Crushed Biaxial Crystal by the Immersion Method," *Jour. Geol. Soc. Tokyo,* XXV (1918), 38–41, fig. 1.

Maximum and minimum values of refractive indices are readily determinable but the intermediate value must be obtained from a carefully oriented section or be computed. In the latter case the angle between the $\mathfrak{c}$ axis and one of the optic binormals must be known. In the present paper is given a method of determining limiting values for β, based on the fact that it must always lie between the two values observed in a crystal section of any orientation. By making observations on many grains, the difference between upper and lower limiting values may be made very small. Using basic plagioclase, the author made determinations to 0.003.

TSUBOI, SEITARŌ. "Notes on Miharaite," *Jour. Geol. Soc. Tokyo,* XXV (1918), 47–58, pls. 2.

The term *miharaite* is given to a lava from the volcano Mihara on the island of Oshima, Idzu. It is a basalt characterized by abundant phenocrysts of bytownite with a few of hypersthene and clino-hypersthene, and a very small amount of augite. The groundmass contains labradorite-bytownite microlites,

augite, magnetite, rare apatite, and negligible glass in the gray varieties, and plagioclase and augite in brown glass in the slaggy kinds. Five chemical analyses are given, all giving high SiO_2 (51.94, 51.13, 51.32, 51.40, and 51.45). The rock is given a new name on account of its occult quartz and normative bytownite. Mineral percentages are not given.

TSUBOI, SEITARO. "A Diagram for Determining Plagioclases." Published in the Japanese language in *Jour. Geol. Soc. Tokyo*, XXVII (1920).

Since cleavage pieces of plagioclase are used in determining their refractive indices, a table giving the values in (010) and (001) is of much greater value than the usual one giving α, β, and γ. These values, computed by Tsuboi and plotted as a curve, are reproduced in the reviewer's *Essentials in the Determination of Rock-forming Minerals and Rocks.*

TSUBOI, SEITARŌ. "On a Leucite Rock, Vulsinitic Vicoite, from Utsuryoto Island in the Sea of Japan," *Jour. Geol. Soc. Tokyo*, XXVII (1920), 91–104.

Describes a porphyritic rock with abundant phenocrysts of sanidine and labradorite, the former slightly more abundant than the latter, less hornblende, augite, and titanaugite, and microphenocrysts of biotite, olivine, and apatite. The groundmass consists of laths of orthoclase and plagioclase and round leucites, with prisms and grains of aegirite-augite, some magnetite, and a trifle glass. An analysis is given which, recast into the norm, gives 4.63 per cent nephelite, 39.59 orthoclase, but no leucite. The analysis is readjusted to give leucite with the approximate proportions orthoclase 21.5, albite 42, anorthite 9, leucite 14, diopside 4.5, magnetite 2.8, ilmenite 1.2, apatite 1.1, olivine 2.7, and zircon 0.11. Compared with the description, however, this does not represent the actual mode (in which the plagioclase is stated to be labradorite), consequently it cannot be classified in the reviewer's system.

TSUBOI, SEITARŌ. "Volcano Oshima, Idzu," *Jour. Col. Sci., Tokyo*, XLIII (1920), art. 8. Pp. 148, 24 photomicrographs on 4 plates, map 1, plate profile 1, figs. 42.

Part of this report was published in the preliminary papers described in the second and third preceding articles. Here is given a geological and historical sketch of the volcano Oshima as well as descriptions of the rock types. These are basaltic bandaites, miharaites (which resemble the preceding but have no olivine), and basalt. Various analyses are given, and some beautiful photomicrographs.

A modification of Becke's method for determining $2V$, here given, greatly simplifies the process. The isogyre is first placed parallel to the horizontal cross-hair of the microscope, and the position of the melatope is determined by two angles, one measured in azimuth from the vertical cross-hair to the melatope by rotating the stage, the other measured from the center by means of a graduated eyepiece and any method similar to that employing a Schwarzmann's axial angle scale. The position of the melatope (A) is marked on a stereographic net and a great circle is drawn through it and the ends of the horizontal line. So far the method agrees with that of Becke. Change the conoscope into an orthoscope and rotate the stage until the section is at extinction and read the angle through which the stage was rotated. This locates one of the vibration directions which is now drawn at the proper angle in the projection. Locate, on the great circle previously drawn, the other melatope by means of an angle equal to that between the first melatope and the line representing the vibration direction. Measure $2V$ in the projection. In the older methods it was necessary to observe a second point on the isogyre, which was difficult. In the Tsuboi method only the position of the melatope is needed. Further, there is no need of using the refractive index in the new method. In Becke's original, five great circles were necessary, and in Wright's modification, four. In Tsuboi's, only one great circle is drawn, and one straight line.

TYRRELL, G. W. "A Contribution to the Petrography of Benguella, Based on a Rock Collection Made by Professor J. W. Gregory," *Trans. Roy. Soc. Edinburgh*, LI (1916), 537–59, pl. 1.

Benguella is one of three provinces of the Portuguese West African colony of Angola. Chemical analyses and complete descriptions are given of the rocks, which are granite, charnockite, dellenite, nephelite-sodalite-syenite, akerite, shonkinite, solvsbergite, ouachitite, and various basic intrusives. The two "charnockites" of Table I are 227′ (new form of reviewer's system) or monzotonalites (granodiorites in limited sense), while the type charnockite from India is 226′, or typical granite. The hornblende-hyperites belong to 3312, as they should. The granite of Table II is 216′, typical granite; the granodiorite is 227′, granodiorite in sense usually used but better monzo-tonalite. The two dellenites computed in Table IV are 227′ for the Angola rock, and 227″ for the one from Sweden. That is, the former is the extrusive equivalent of a granodiorite, while the latter is the extrusive equivalent of a quartz-monzonite. The shonkinite of Table V is 2113, which is not according to definition of shonkinite as originally give by Pirsson, for in that the dark constituent must form more than half the rock, consequently it must be in Class 3, as actually is the type Montana specimen given in the same table. The Angola rock falls into the group with pulaskites although the feldspathoid in the latter rock was given by Williams as nephelite or its decomposition product analcite.

TYRRELL, G. W. "Further Notes on the Petrography of South Georgia," *Geol. Mag.*, III (1916), 435–41.

Describes various rocks from South Georgia. The sediments are slates and phyllites, arkoses and grits. The igneous rocks are epidorite, dolerite, basalt, alaskite, quartz-felsite, lavas and tuffs of doubtful affinities, epidosite, and augitite. So far as petrographic evidence goes, the question whether South Georgia belongs to Suess' "Southern Antilles," or whether it is a remnant of an old sunken continental land remains unsettled.

TYRRELL, G. W. "The Petrography of Arran," *Geol. Mag.*, III (1916), 193–96.

Pitchstone xenoliths in a basalt dike throw some light upon the question of the temperature of lavas. The phenocrysts of quartz have suffered hardly at all, the andesine has had a softening on the margins and fissuring in the interiors, while the orthoclase shows fusion around the margins and along cleavages, producing a yellow or grayish glass, differing from that of the groundmass. The temperature of the intruding lava is therefore thought to have been between 1170° C. and 1375° C.

TYRRELL, G. W. "Some Tertiary Dykes of the Clyde Area," *Geol. Mag.*, IV (1917), 305–15, 350–56, figs. 3.

Describes a dike-rock consisting of phenocrysts of anorthite in a groundmass of labradorite, enstatite and augite, and much glass. The glass indicates orthoclase, silica, and albite. Chemically this rock approaches andesite, from which it differs in its more basic phenocrysts. It is here called *Cumbraite.* It differs from Thomas and Bailey's Inninmorite in containing enstatite as well as augite. While the name cumbraite is proposed by Tyrrell, he says: "Whether these terms should obtain a circulation outside the discussion of the British Tertiary petrographic province is a question beyond the scope of this paper. My own opinion is that they should not."

TYRRELL, G. W. "The Trachytic and Allied Rocks of the Clyde Carboniferous Lava-Plateaus," *Proc. Roy. Soc. Edinburgh,* XXXVI (1917), 288–99.

Among the lavas of the Scottish Carboniferous, true andesites and rhyolites are absent, trachyte and allied rocks are present in subordinate quantities, while basalts predominate. In this paper are brief descriptions of albite-bostonites, albite-trachytes, albite-keratophyres, bostonites, keratophyres, quartz-keratophyres, felsite, and phonolite. Ten analyses, one of bostonite previously unpublished, are given.

TYRRELL, G. W. "The Igneous Geology of the Cumbrae Islands, Firth of Clyde," *Trans. Geol. Soc. Glasgow*, XVI (1916–17), 244–74, figs. 5.

Most of the igneous rocks of the Cumbraes are of Lower Carboniferous age. They are predominatly basaltic and originally covered from 2,000 to 3,000 square miles.

TYRRELL, G. W. "The Picrite-Teschenite Sill of Lugar," *Quart. Jour. Geol. Soc.*, LXXII (1917), 84–131, pls. 2.

The Lugar sill in the west of Scotland is found to be made up of a complex of rocks belonging to the analcite series. It forms a mass 140 feet thick and was intruded into cold rocks, as shown by chilled contacts at top and bottom, giving a fine-grained teschenite for a thickness of 10 feet. Beyond the margins, both top and bottom, the rock passes into coarse teschenite. In the interior the sill is divided into at least three bands by some process of differentiation or by successive intrusions, giving first a band of ultra basic rock—picrite and peridotite of coarse texture—occupying the major part of the whole mass. The picrite forms the upper part of the ultrabasic stratum, the peridotite the lower. Above the picrite is a band about 10 to 15 feet thick of fine-grained, basic, nephelite rock of the theralite family. Overlying the picrite, in places, is a peculiar rock to which the name *lugarite* has previously been given. It appears to be intrusive in the picrite, for veins of similar material traverse the latter rock in various places. Three of the teschenites are 2319′ of the reviewer's system, and two are 3320, the difference being the absence of orthoclase and the predominance of the dark constituents in the latter. Two chemical analyses are given as well as five more calculated from Rosiwal measurements. Two lugarites are 2320. (A rock described as lugarite in *Geol. Mag.*, 1915, 363, is here called a lugarite-like rock. It is 2218′.) One chemical analysis and two calculated analyses from Rosiwal measurements are given. As for the cause of the differentiation, the author thinks that the hypothesis of sinking of heavy crystals is well attested in the Lugar magma as a whole, but that the differentiation took place prior to its emplacement. The material was injected in successive intrusions, the teschenite first in cold rocks and formed the fine teschenite borders. While still cooling, but probably already solid, the picrite was intruded along its center plane. Here differentiation took place mainly by the sinking of olivine-crystals. Later, while probably still partly liquid, it was intruded by a small mass of lugarite.

VELDE, LUISE. "Die silikatischen Einschlüsse im Basalte des Bühls bei Kassel," *Abhandl. d. Senckenberg. Naturf. Gesell.*, XXXVII (1920), 111–35, pls. 4.

The silicic inclusions in the Bühl basalt in many cases preserve the characteristics of the original rocks from which they were derived, namely, sandstones

and slates. The great majority of the rocks are strongly metamorphosed and in them have been developed sillimanite, corundum, spinel, magnesium-diopside, scapolite, cordierite, and plagioclase. In this work the various inclusions are petrographically described and several chemical analyses are given. The most abundant inclusions are quartz-sillimanite.

C. H. BEHRE, JR.

VOGT, J. H. L. "Die Sulfid-Silikat-Schmelzlösungen," *Norsk. Geologisk Tidsskrift*, IV (1917). Pp. 97, figs. 13, and several tables and analyses.

VOGT, J. H. L. *Die Sulfid-Silikat-Schmelzlösungen: Die Sulfid-schmelzen und die Sulfid-Silikatschmelzen.* Christiania, 1919. Pp. 131, figs. 45, and numerous tables and analyses.

The first of these two papers is essentially a résumé, written in 1917, of extensive work on sulphide-silicate solutions, giving the results obtained to the date of its publication. The second paper presents in detail the data of the earlier one, and embraces additional facts gleaned through two more years of work on the same subject; it is more detailed than the earlier publication and will be reviewed here first. The reviewer believes that with such comprehensive work as this, adequate abstracts are impossible. He strongly advises a careful perusal by metalographers, economic geologists, geochemists, and physical chemists. He wishes to commend the completeness of these studies.

Previous experiments have shown that certain sulphides, such as Sb_2S_3, Bi_2S_3, and Ag_2S, have a lower melting point than even those silicates with the lowest melting points. Other sulphides, such as those of lead, copper (Cu_2S), and iron (FeS) and pyrrhotite, have melting points about like those of the least refractory silicates and slightly higher than some of the eutectic mixtures of silicates with low melting points. Other sulphides finally, such as those of zinc, manganese, barium, and calcium, have melting points markedly higher than those of the more common natural silicates. Under-cooled sulphide mixtures or solid solutions of sulphides (sulphide glasses) are unknown.

From a study of the latent heat of fusion it appears that the sulphides PbS, Ag_2S, Cu_2S, FeS are not highly polymerized. It is found, further, that Fe_3O_4 is only slightly soluble in melts of Cu_2S; this is corroborated by the crystallization sequence as observed in magmas, for magnetite (and ilmenite) crystallize very early indeed from a pyrrhotite- or pyrite-bearing magma. Silicates are soluble in FeS or Cu_2S melts to only a very minor degree.

After a study of the relations between the various sulphides and their eutectics, the writer demonstrates that a eutectic is also possible in solutions of calcium sulphide (or manganese sulphide) in various silicates, such as melilite

and olivine. For example, in sulphide-rich melts with melilite, much of the mass of sulphide crystallizes out before the corresponding spinel, and the remainder crystallizes synchronously with the spinel.

In a solution of calcium magnesium silicate, calcium sulphide in the amount of 2.3 per cent lowers the melting point about 50°. By calculating the molecular depression it is found that polymerization of the sulphides of calcium and manganese in silicate melts is essentially nil; in fact, in the silicate solutions an extensive electrolytic dissociation more probably takes place.

Somewhat similar results as to the presence of a eutectic in solutions of zinc, aluminum, and iron oxides are discussed. In a melt bearing zinc sulphide, zinc spinel, and melilite, the order of crystallization follows the order of naming, as above; if, however, olivine be present instead of melilite, and only a very little sulphide, the order of crystallization is spinel, olivine, and sulphide.

In other slags the presence of copper and its relation to chondri-like structures, and to iron sulphide-bearing silicate solutions were studied. An interesting feature is the concentric arrangement of iron sulphide inclusions in hexagonal plates of biotite. From these observations it is found that Cu_2S is wholly insoluble or at best only slightly soluble in silicate melts rich in iron sulphide—attributable possibly to the presence of a common ion. Various conclusions drawn in this part of the investigation are interesting not only to the geochemist, but to the metallurgist as well.

Some space is also devoted to the crystallization of apatite and ore—the so-called "telechemical" minerals—those only distantly related to the silicate minerals.

The foregoing facts may be gleaned from the publication of 1919. The paper of 1917 briefs most of these observations, and adds considerable material on the part of sulphides in eruptive magmas—an application of physical chemistry to systematic petrogenesis.

Pyrite appears to crystallize very early from magmas, and has a higher melting point than magnetite. Pyrite generally precedes pyrrhotite in the normal sequence of crystallization; it also precedes chalcopyrite, which generally follows magnetite when all three sulphides crystallize from a melt. As previously observed, magnetite is only very slightly soluble in pyrite-rich melts; hence iron oxides are rare or absent in such melts.

A study of the norite-type magmas leads to the conclusion that the predominant mineral generally crystallizes first; thus, in plagioclase-rich norite, plagioclase is automorphic; in olivine-plagioclase, plagioclase-rich rock, plagioclase; in olivine-rich olivine-plagioclase rocks, olivine is automorphic, and so on. The physical chemistry of the several systems normally present in a gabbro-norite magma is summarized, and the writer believes in a eutectic for rocks of the gabbro-norite group, this eutectic, however, being expressed by a line, rather than by a point.

The rather constant appearance of pyroxenites and peridotites in close association with nickel-pyrrhotitic deposits, as at Sudbury, is thought to be

indicative of a eutectic mixture. Various conclusions regarding the order of crystallization in such magmas are drawn from petrographic data. The crystallization temperature for the normal norites is calculated (estimated) to lie between 1200° and 1300° at an atmosphere's pressure. From norite magmas acid dikes are distinct differentiation products, hence very generally associated with nickel-bearing norite. Petrographically the writer seeks to establish in such basic rocks (of the picrite-norite series) the increase of the nickel content with increase in hypersthene or bronzite; all the nickel deposits associated with peridotite have an exceptionally high nickel content.

The sulphides in the norite masses are supposed to be precipitated from the melts with decreasing temperature and then to settle to the bottom; the small amount of sulphides remaining later crystallized with the silicates and was not wholly segregated.

This work has demonstrated: (1) that the origin of nickel-pyrrhotite deposits may be explained by the laws affecting a system liquid-liquid; (2) that the leucocratic acid pyritiferous dikes correspond to the end-product of crystallization in a noritic magma bearing a slight amount of free quartz; (3) that the numerous occurrences of a chalcopyrite-rich sulphide mixture in locally distributed veins, especially such as are limited to the border phases of the rock, depend upon the fact that the chalcopyrite was concentrated in the end magma through progressive solidification of the sulphide constituents.

REVIEWS

Description géométrique des Alpes Françaises, Annexe du Tome second. By P. HELBRONNER. Six panoramas dessinés et peints par l'auteur, 23 planches dans un carton in-folio. Paris: Gauthier-Villars, 1921.

Gauthiers-Villars of Paris have, in this portfolio, put on the market colored panoramas of the French Alps which for both accuracy and beauty excel anything which has hitherto been produced. These panoramas have been drawn and colored as aquarelles by Paul Helbronner upon the basis of a trigonometric survey which this accomplished map-maker, Alpinist, and artist has made. In the course of this work, he found it necessary to ascend with his instruments all the high and difficult peaks of the region. In all, the panoramas consist of twenty-three plates in color joined in six groups. The largest of the panoramas is a complete tour of the horizon from the summit of Mont Blanc and consists of thirteen plates making a picture 19 ft. 6 in. in length. Two others—Mont Blanc from the Mont-Maudit and Mont Blanc from the Col du Géant—consist each of three plates of the same size as the others. Under each of the panoramas is an outline-drawing from which each peak may be identified. The coloring of these remarkable panoramas is superb while faithful to nature, as will be testified to by anyone who has climbed in these regions. The publication of the portfolio marks an epoch in the history of reproduction in color. The panoramas are all well suited for framing.

W. H. HOBBS

Coal. By ELWOOD S. MOORE. New York: John Wiley & Sons, March, 1922.

This is primarily a volume for the mining student and the engineer who is in charge of coal-mining operations, but it should also be of interest to every geologist. It brings together the best of a varied literature and places it at the disposal of all in usable form.

Neither time nor space is wasted in the introductory chapter. From a brief history of the subject the author starts out energetically to discuss the megascopic and microscopic properties of coal and then passes naturally into a discussion of its chemical composition. The best and latest methods of sampling are given in sufficient detail to enable a man

to follow them satisfactorily. A similar statement might be made regarding the methods of chemical analyses and, in later chapters, on mining methods.

It is unfortunate that with all our classifications of coal none seem to meet with general approval. Probably the best is that adopted by the Twelfth International Congress of Geologists, and which was originally developed by D. B. Dowling of the Canadian Geological Survey. The author favors a classification based upon more than two factors as best meeting the requirements, but admits the inadequacy of those now in use.

The origin of coal, through the transformation of vegetal matter accumulated in swamps, is discussed in considerable detail. The amazing rapidity of the metamorphic processes in any such accumulation is illustrated by the pebbles of coal occurring within the Coal Measures and the alteration of the upper end of a mine prop which had been subjected to high pressure for thirty years, during which time it also felt the effects of the heat from a fire in an adjacent part of the mine. The upper part of the prop and the cap wedge had a jet black color, a bright glossy luster, and conchoidal fracture. Evidently the intensity of the other factors may compensate for the lack of a large portion of the time element usually regarded as essential in the formation of the higher grades of coal.

A chapter is devoted to the vegetation of the coal periods and deals chiefly with the extinct forms. The author then takes up the structural conditions existing in coal seams, the location and determination of thickness of beds, and the value of coal lands. The latest mining methods and the preparation of the coal and coal products for the market are given due consideration. Finally a summary of the geology of the coal fields and the coal resources of the world completes the volume.

The book is adequately illustrated by well-chosen cuts, maps, and photographs. The plan of the text is admirable and the author handles his subject with good clear English, which is free from useless repetition. This has made it possible for him to get a remarkable amount of information into a single volume. Considering its size and scope, it is certainly one of the best texts on coal that has been published.

C. R. S.

Structure in Paleozoic Bituminous Coals. By REINHARDT THIESSEN, United States Bureau of Mines, Bulletin 117, Washington, 1920. Pp. xiii+296. Pls. CLX.

An extensive historical review of previous studies of woody structure in coal is followed by a detailed description of the technique of the

author's investigation. A study of the origin of peat follows, which throws some light on the way in which coal was formed in Paleozoic times. The author's study of the structure of coal embodies the results of his examinations of a number of different Paleozoic coals. Particular attention is given to microscopic studies, many of which were made with a magnification of 1,000 diameters, approaching the limit of visibility.

The text is accompanied by 160 plates, many of which contain several illustrations,and a bibliography of publications on the composition of coal.

An enormous amount of valuable information on the composition of coal has been accumulated in this bulletin. Many side lights on plant life during the Paleozoic are brought out by the study of the spores and other morphological elements of the coal. Biologic factors like the origin of rootlets and the existence of fungi in Paleozoic times, are revealed.

There are a number of theories concerning the origin of coal, but we are yet unable to form a conclusive conception of this interesting geological process. Thiessen's paper supplies a great amount of information which brings us a step nearer to a satisfactory conception.

A. C. N.

Contact-metamorphic Tungsten Deposits in the United States. By Frank L. Hess and Esper S. Larsen. United States Geological Survey, Bulletin 725-D, 1921.

Of the 5,000 tons of tungsten concentrates (reckoned as 60 per cent WO_3) produced in the United States in 1918, about 1,400 tons was in the form of scheelite ($CaWO_4$) from contact-metamorphic deposits. Most of these deposits are along the western side of the Great Basin in California and Nevada but there are scattered deposits near Great Salt Lake and in Arizona, New Mexico, and Oregon. Their development has been recent, the first of the type being discovered in 1908. During the European war most of them were active producers but by 1920 all had lapsed into idleness because of the severity of competition with imported concentrates and richer American ores, combined with the great depression in the steel industry.

The contact-metamorphic tungsten deposits are nearly all at or near the contact between quartzose igneous rocks, principally granodiorites, and limestones. In a number of districts the deposits are clustered about several small granite outcrops close together, which suggest the presence of a larger granite body beneath.

The silicate minerals are those usual in contact-metamorphic deposits, except that minerals carrying boron appear to be absent and magnetite and hematite are notably rare.

The eccentric distribution of the deposits along some igneous contacts is correlated with the presence or absence of fractures which could serve as channels for the metamorphosing solutions, but other eccentricities such as the presence of chunks of unaltered limestone in the intrusive are not readily explained. Where the intrusive rock is in contact with a large body of sediments the contact-metamorphic rocks may follow the contact rather regularly, or may replace certain beds in the sediments, or may follow fissures crossing them. Unlike many contact-metamorphic deposits which are notably compact, these commonly contain vugs some of which attain the dimensions of caves in which a man can stand upright. These are not the result of solvent action subsequent to metamorphism but were formed during metamorphism, and are characterized by crystals of quartz some of them a foot long projecting inward from their walls.

Contact metamorphism has usually affected the igneous rock as well as the limestones, but the metamorphic zone is much narrower in the intrusive than in the limestone and is much more siliceous being made up mostly of quartz with subordinate dark silicates of the same varieties that characterize the adjacent altered limestone. A distinct zoning is usually perceptible in the alteration of the limestone. The zone nearest the intrusive is characterized by dark-colored iron-bearing silicates—iron-bearing garnet, epidote, pyroxene, hornblende, etc., with calcite and quartz and minor amounts of other minerals. This zone is the chief host of the scheelite.

Beyond this zone comes a zone characterized by light-colored silicates poor in iron, tremolite and wallastonite being the commonest of these silicates. Colorless diopside, scapolite, colorless garnet, and other silicates are present in less abundance. Calcite is very abundant. Scheelite is absent. The zone of light-colored silicates grades outward into the marble that forms the outermost part of the contact-metamorphic aureole.

Evidences are present that in many of the deposits the minerals were not deposited contemporaneously, but that one mineral followed another in a regular sequence. The details of the successive replacements were not worked out microscopically, but in general it appears that garnet was one of the first to be deposited and that sulphides were among the last.

The authors propose the name "tactite" for the rocks and ores developed by contact metamorphism nearest the intrusive (Latin, *tactus*, "touch"). This term seems well chosen and may prove a convenience. It should be noted that the authors designate as "tactite" only the zone

of dark silicates next the intrusive, and do not apply the term to the zone of light-colored silicates or to the marble.

No evidence of enrichment through the action of meteoric waters was noted in any of the deposits. Leaching is shallow.

The average tenor of the deposits worked near Bishop, California, is about 0.5 per cent of WO_3; ore mined in the Mill City, Nevada, district averaged about 2 per cent of WO_3.

E. S. Bastin

Geology of the Non-metallic Mineral Deposits Other Than Silicates. Vol. I. Principles of Salt Deposition. By A. W. Grabau. First edition. New York: McGraw-Hill Book Co., 1920. Pp. xvi+435, figs. 125.

This volume is a treatise on applied stratigraphy. The author designates it as "a hand-book of salt-geology," using the term salt to include phosphates, nitrates, borates, and similar deposits, as well as common salt.

The author discusses first the sea as a source of saline deposits, basing a number of his conclusions on the careful work by Van't Hoff on the famous Stassfurt deposits. This is followed by a well-illustrated chapter concerning the conditions by which sea salts are deposited in nature, emphasis being placed on their organic deposition.

In the discussion of lagoonal deposits, it is concluded that many of the older salt deposits, generally believed to have been formed after the manner postulated by the bar theory, cannot be accounted for in this way, inasmuch as they are non-fossiliferous. Lagoonal deposits, such as those forming in the Karatugas Basin, contain fossils.

A chapter is devoted to the classification of terrestrial salts, and the larger portion of the book is devoted to a discussion of their origin, method of concentration, and distribution. Throughout the book numerous salt lakes and salt basins of various types are described, and their deposits discussed.

Attention is given to the mooted questions of the origin of nitrates, phosphates, and dolomites, and the several theories which have been advanced to explain them are stated.

In the chapter on "Deformation of the Salt Bodies," the author favors the view of Rogers that the salt domes of Louisiana and Texas are of exogenetic origin, but doubts whether all the characteristics of salt domes can be accounted for without the action of endogenetic forces.

The last chapter is devoted to an interesting discussion of the "Conditions of Salt Deposition in Former Geological Periods." In this chapter, and indeed throughout the book, attention is directed to the stratigraphic and paleontologic characteristics of the various types of deposits, the object being to prepare the reader for the stratigraphic chapters which are to follow in Volume II.

The book is a valuable contribution to the science of salt deposits, and should prove of great service to students of economic geology.

W. T. B.

Upper Cretaceous Floras of the Eastern Gulf Region in Tennessee, Mississippi, Alabama, and Georgia. By E. W. Berry. United States Geological Survey, Professional Paper 112, Washington, 1919.

The bulk of the flora is from the Tuscaloosa formation, and this paper is devoted principally to its elucidation and is to be regarded as a preliminary report, because Professor Berry's work was of a reconnaissance nature. Later, when the abundant workable clays of the Tuscaloosa formation are developed for economic purposes, many new localities of fossil plants probably will be discovered and additional representatives of its flora. One hundred and fifty-one species, representing eighty-seven genera from the Tuscaloosa formation, are described. The three other subdivisions of the Upper Cretaceous, the Eutaw formation, the Selma chalk, and the Ripley formation, contributed but meagerly to Berry's collection.

In comparing the Tuscaloosa flora with the European Upper Cretaceous floras, Berry finds that eighteen identical species are found in the European Cenomanian, two in the Turonian, and four in the Senonian. Therefore, the evidence of the floras is overwhelmingly in favor of the pre-Senonian and pre-Montana age of the Tuscaloosa and allied floras. Thirty Tuscaloosa species are found in the Atane beds of Greenland, and ten in the Patoot beds of the same island. The book is amply illustrated with plates.

A. C. N.

The Mineralization of the Copper Shales. By F. Beyschlag. Zeitschrift für praktische Geologie. January, 1921. Pp. 1–16.

In this article Dr. Beyschlag brings forward very cogent arguments in support of the view that the famous copper deposits of Mansfield, Germany, are not of sedimentary origin, but are younger than the rocks

which inclose them and where deposited by solutions from magmatic sources and later enriched through the agency of descending solutions.

The copper ores occur in three positions: First, in the highly bituminous and pyritic beds of the copper shale (*Kupferschiefer*); second, in the immediately underlying Zechstein conglomerate and the Weissliegende—the latter forming the upper, bleached portion of the Rotliegende; third, in "rucken" or veins cutting any or all of these Permian sediments.

The dominant metallic minerals in all three situations are chalcopyrite, bornite, and chalcocite. Minor components are pyrite, galena, niccolite, safflorite ($CoAs_2$), and some others. In the copper shale the ore is mainly the so-called "Speise," a fine dust of sandlike ore particles in the rock. Strings and thin plates of sulphides also occur usually parallel to the bedding but elsewhere cutting it at small angles or uniting to form networks of sulphides. Bean and kidney-shaped masses of sulphides also occur. The microscope shows clearly that these sulphides have developed by replacement of the shales. Nowhere are the sulphide masses rounded as might be expected if they were original components of a mechanical sediment. In the Zechstein conglomerate and Weissliegende the ore minerals characteristically form "sand ore" 1–3 cm. thick immediately beneath the copper shale. In the sand-ore spaces between the sand grains are occupied by chalcopyrite and more rarely bornite and chalcocite. Heavy impregnations grade into mere sprinklings of sulphides. In more clayey beds segregations and plate-like masses of sulphides occur. The "rucken" or veins occupy faults of a few centimeters to 100 meters displacement cutting the sediments. Many of them are richly mineralized while others are lean or barren. The maximum mineralization of the veins is in the vicinity of the copper shale and frequently the ore is confined to that part of the vein between the displaced portions of the copper shale. Two generations of ore minerals are recognizable in the veins, the older generation with nickel and cobalt arsenides, calcite, molybdenite, and rarely pitchblende, and the younger generation with copper sulphides and barite.

If it is assumed that the ores in the copper shale and Zechstein were deposited on the sea bottom at the time these sediments were laid down, it is necessary to assume that copper-bearing solutions were contributed to the sea by streams from the land or by submarine springs. The land areas of that period contained no rocks which by weathering or otherwise can be supposed to have yielded copper-rich solutions. If submarine springs had been the source of copper-bearing solutions the ores

in the sediments should presumably have been less uniform over wide areas than is actually the case.

The author of the paper turns therefore to igneous sources for an explanation of the ores. He points out that the Permian intrusive rocks of Europe are very generally copper-bearing and attributes the primary deposition of copper in the Mansfield deposits to solutions coming from the same magmatic source that at an earlier period yielded the eruptive rocks that form part of the Rotliegende. Cupriferous mineralizing solutions, according to Beyschlag, ascended along the vein fractures and spread laterally through and beneath the copper shale depositing chalcopyrite in the sediments by the filling of pores and by replacement, the bitumen and pyrite in these beds being instrumental in the ore precipitation. They also deposited chalcopyrite, cobalt, and nickel arsenides, molybdenite and rarely pitchblende in the fault fractures.

The writer points out that mineralization in the copper shale and Zechstein is greatest where veins cutting these formations are numerous and close together.

Although Beyschlag does not emphasize particularly the genetic significance of primary mineral composition, to the reviewer the presence in the veins of cobalt and nickel arsenides, of molybdenite and of pitchblende is highly suggestive of a magmatic origin for the mineralizing solutions.

Of the primary ores developed by the processes just described only remnants now remain. Most of the primary ore minerals have been replaced by the rich copper minerals, bornite and chalcocite, through the agency, Professor Beyschlag believes, of descending meteoric waters—the familiar process of downward sulphide enrichment. As evidence of such enrichment, it is shown that much if not most of the bornite and chalcocite is a replacement of chalcopyrite and drawings are presented showing such replacements. Bornite is characteristically the first mineral to replace chalcopyrite; chalcocite then replaces bornite. Further, there is a marked falling off in the abundance of the rich copper minerals in depth.

Of fundamental importance is the conclusion that the ores in the sediments and in the veins were formed contemporaneously, a conclusion based mainly on the restriction of ore in the veins to the vicinity of the ore-bearing beds and conversely the greater development of ore in the beds where they are cut by numerous and close-spaced veins.

E. S. Bastin

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WORLD-ROMIC SYSTEM

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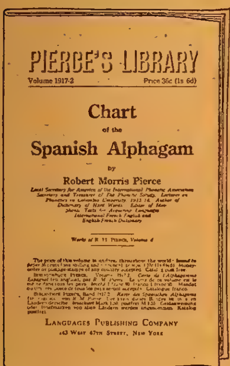

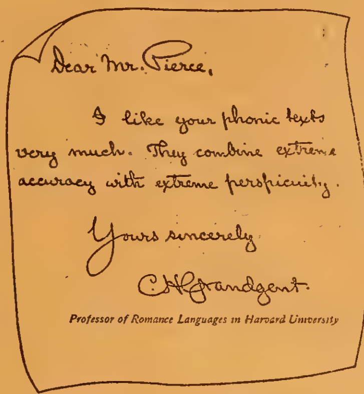

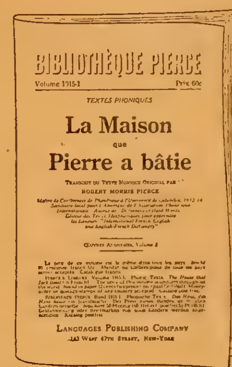

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